A SENSITIVITY ANALYSIS OF UNCERTAINTY IN THE SPATIAL RESOLUTION OF THE UNDERLYING DATA USED FOR ESTIMATING SOIL EROSION SUSCEPTIBILITY IN NEW ZEALAND

A thesis

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by

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Dedicated to my Grandfather and Grandmother Nehring, as well as my Uncle Loran Nehring and cousin Ann Collins, who all passed away while I was studying abroad in New Zealand.

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List of Abbreviations

AOI	*Area of Interest*
CAR	*Conditional Autoregression*
COSP	*Change of Support Problem*
DEM	*Digital Elevation Model*
DSIR	*Department of Scientific and Industrial Research*
DOQ	*Digital Orthophoto Quads*
EPA	*Environmental Protection Agency*
ESC	*Erosion Susceptibility Classification*
GDP	*Gross Domestic Product*
GIS	*Geographic Information System*
GPS	*Global Positioning System*
GWR	*Geographically Weighted Regression*
IS	*Information System*
LENZ	*Land Environments of New Zealand*
LiDAR	*Light Detection and Ranging*
LINZ	*Land Information New Zealand*
LRI	*Land Resource Inventory*
LRIS	*Land Resource Information System*
LUC	*Land Use Capability*
MAUP	*Modifiable Areal Unit Problem*
MFE	*Ministry For The Environment*
MSS	*Multispectrum Scanner System*
MWD	*Ministry of Works Department*
NES	*National Environmental Standards*
NWASCO	*National Water and Soil Conservation Organisation*
NZ	*New Zealand*
NZGO	*New Zealand Geospatial Office*
NZLRI	*New Zealand Land Resource Inventory*
RMA	*Resource Management Act*
ROI	*Region of Interest*
SCRCC	*Soil Conservation and Rivers Control Council*

US	*United States of America*
USDA	*United States Department of Agriculture*
VB	*Visual Basic*

Abstract

This study investigates the effect of changes in map scale on the error in the development of areal map units and their associated erosion severity measurements of New Zealand's (NZ) Land Use Capability (LUC) surveying system. A map scale of 1:50,000 was used in the underlying data (i.e., a LUC survey) of an Erosion Susceptibility Classification (ESC) system, which was developed by Bloomberg and others (2011) of the University of Canterbury for the Ministry for the Environment's (MFE) 2010 proposed National Environmental Standard for Plantation Forestry. The ESC was intended for local erosion management decisions, yet most literature would classify the map scale of 1:50,000 as more appropriate for regional management issues. Thus, this study will test two finer 1:10,000 scale datasets against the current 1:50,000 national LUC areal map units and their erosion severity measurements of the underlying data for the ESC system, to quantify the level of agreement.

This study first attempted to identify a unique discriminating parameter of high erosion severity. A case study was conducted in the Sherry River catchment, located in the Tasman District of the South Island, NZ. The Sherry River Case Study had two aims; the first was to investigate the correlation between the Melton ratio and LUC erosion severity. This was accomplished by calculating the Melton ratio, a tested morphometric factor that describes basin (watershed) ruggedness, using Irvine's (2011) Geographic Information Systems (GIS) debris-flow model. The product of this GIS debris-flow model, a calculated Melton ratio ≥ 0.50 with the areal extent outlined by a River Environment Classification (REC) order one polygon, were designated the areas of interest (AOIs). The Melton ratio was then tested against LUC erosion severity using the Spearman's Ranked Correlation Coefficient, within the designated AOIs. A field investigation was conducted to verify debris-flow in GIS identified AOIs. Only five of the thirteen AOIs identified showed evidence of debris-flow. Two were un-checked due to accessibility and the others had a high degree of fluvial activity, which indicates a high probability that surface evidence of alluvial erosion deposition was erased. Nominal association between the two measurements of erosion (Melton ratio and LUC erosion severity) was found at the map scales of 1:50,000 or 1:10,000. Therefore the Melton ratio was not recommended as an independent parameter of erosion severity.

The second aim of the Sherry River Catchment study was to assess the sensitivity of empirically generalised LUC areal map units and their erosion severity measurements to spatial resolution, that is, what is the effect of agreement between the smallest measurable value when looking at LUC map units and their erosion severity measurements recorded at two different map scales. A hard classification accuracy assessment was chosen to accomplish this objective. An accuracy assessment is a statistical model, which provides a probability of error (uncertainty), in essence a goodness-of-fit measurement, and quantified the agreement between a sample and reference dataset. This was accomplished by the calculation of an Overall accuracy (i.e., overall thematic agreement), Producer's accuracy, and a User's accuracy analytical statistics. The Producer's accuracy refers to the probability that an area of sampled erosion severity category in the sample map is classified as such according to the reference map, while the user's accuracy refers to the probability that a point labelled as a certain erosion severity in the sample map has that severity rating in reality (i.e., according to the reference map). An accuracy assessment also includes a second goodness-of-fit test, the Kappa statistic ($\widehat{K}$), which measures the agreement between the sample and references map as well as chance agreement. An accuracy assessment of the AOIs within the Sherry Catchment Study area using an 85% significance criterion was conducted. This accuracy assessment investigated a sample LUC survey measured at the map scale of 1:10,000, as compared to the referenced underlying data of the ESC (1:50,000 map scale). Overall accuracy was marginal (69%) with equally marginal levels of Producer's and User's accuracy. The Kappa statistic showed a marginal level of significance according to Landis and Koch (1977) ($\widehat{K}$ = 44%). The disagreement seen between the two LUC surveys, which were empirically developed using different map scales, provides evidence of high spatial resolution sensitivity, when comparing areal map units and erosion severity measurements.

To further investigate evidence of spatial resolution sensitivity in LUC surveying, a second case study was conducted using a LUC survey across a broad geographical area of the Manawatu-Wanganui Region of the North Island, NZ. A sample dataset from the LUC survey, empirically generalised at 1:10,000 map scale by the Horizons Regional Council, was compared to the referenced underlying data of the ESC. There was a moderately-strong consistency found between the assessors of each LUC survey using Spearman's Ranked Correlation Coefficient. This provides evidence of limited surveyor bias, as each map was made using empirical judgment. The accuracy assessment's overall agreement was 63% and as for the previous case study, had equally low Producer's and User's accuracy levels. The Kappa statistic for this case study was $\widehat{K}$ = 46%, a moderate chance agreement. This evidence, along with the evidence provided by the Sherry River Catchment Case study, suggested that the MFE's ESC system is sensitive to changes in map scale and that any decision based on it will have different results when its underlying data is produced at different spatial resolutions. It is therefore recommended that MFE reassess the map scales and resolutions of its underlying data, given that the ESC's purpose is for local level environmental management, before imposing the system as a regulatory requirement in the National Environmental Standards for Plantation Forestry.

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Chapter 1 Introduction

1.1 Background

This study investigates the effect of changes in map scale on the error in the development of areal map units and their associated erosion severity measurements of New Zealand's (NZ) Land Use Capability (LUC) surveying system.

This thesis investigated the sensitivity of New Zealand's Land Use Capability (LUC) areal map units and their measured erosion severity values to changes in surveyed map scale. Map scale is defined as the ratio between a measured distance on a map and the real world distance which the measurement represents (Jones, 1997, p. 123). LUC map units and their erosion severity values form the basis (underlying data) of an erosion susceptibility classification (ESC) system developed for NZ's environmental management. The intent of this study was to investigate the level of spatial uncertainty by pair-wise comparison of a finer map scale (1:10,000) LUC surveyed data with coarser (1:50,000 scale) data used as the underlying data of the ESC system. In doing so, this study provides an understanding of the sensitivity of map scale to the spatial resolution of NZ's ESC system. Spatial resolution being the smallest distance or measurable value over which it is possible to record changes between two or more spatial units (Jones, 1997, p. 122).

In September of 2010, the Ministry for the Environment (MFE) released a proposed National Environmental Standard (NES) for Plantation Forestry. The intent of the NES for Plantation Forestry was to implement a nationwide consistency of resource management policy and rules for plantation forestry, providing direction for farm/plantation level management decisions (MFE, 2011c).

An important aspect and purpose of the proposed NES for Plantation Forestry was the understanding of erosion susceptibility. Erosion susceptibility is defined as the "… interaction of predisposing factors and preparatory factors, determining the intrinsic susceptibility of a land unit to erode" (Bloomberg et al., 2011). Predisposing factors include the lithology and topographic characteristics of a unit of land. Preparatory factors related to plantation forestry may include the harvesting of trees, tilling or scraping soil for planting operations, road and landing construction, as well as interruption of drainage patterns.

Bloomberg and others (2011) produced an erosion susceptibility classification (ESC) system, which mapped where erosion was likely to occur for planning and consent purposes (Bloomberg et al., 2011; MFE, 2011c). At present the ESC system is fixed at a 1:50,000 map scale (MFE, 2011c), not suitable for local erosion estimation (as explained by: Jessen, 1987; Lynn et al., 2009; Saunders & Glassey, 2007). This thesis focused on developing a further understanding of the sensitivity of LUC areal map units and their annotated erosion severity categories, when map scale is changed from a coarse 1:50,000 to a finer 1:10,000 scale.

To fully comprehend this "scale problem," context must be given. The following sections will introduce and define a succession of topics, which provide a framework for the development of Bloomberg and others' (2011) ESC system. These sections include erosion, the NZ Land Resource Inventory (NZLRI), NZ's LUC system, and an introduction to the proposed ESC system. This will be followed by the thesis scope and objectives, as well as the thesis strategy.

1.1.1 NZ Erosion

Erosion is a present and extensive problem in NZ (Eyles, 1983). NZ's landforms are still geologically young (Molloy, 1998, p. 13) and always in some state of erosion, often caused by environmental or anthropogenic factors or some combination of both. The youth of NZ's landforms can be quantified when measuring the current regional uplift at the Alpine Fault, in the Southern Alps of NZ. Here, an uplift rate of 8-10 mm a year can be measured through the assessment of oxygen isotopes and stratigraphy based measurement methods (Chamberlain, Poage, Craw, & Reynolds, 1999; Simpson, Cooper, & Norris, 1994). This uplift is a result of a subduction zone, which is presently being formed by the collision of the Indian/Australian and Pacific tectonic plates. Volcanic activity derived from this subduction zone has contributed to half of NZ’s North Island landscapes and soils (Molloy, 1998, p. 13).

NZ’s landscape consists of 70% hill country (slopes of 12-28°) or steep lands (slopes > 28°) (Molloy, 1998, p. 13). Slope is a key predisposing factor of erosion (Bloomberg et al., 2011; Lynn et al., 2009). The North Island is dominated by hills, whilst the South Island has more steep lands.

NZ’s climate, soil, and underlying bedrock properties provide the optimal conditions for multiple erosion types. These erosion types include surface, mass movement, earth flow, and fluvial erosion.

1.1.2 New Zealand Land Use Inventory

To appreciate the spatial characteristics and attributes of NZ’s physical landscape geomorphologists, soil researchers, and other physical scientists have inventoried and mapped the details needed to study erosion and its severity. These details populate a geospatial database (the NZLRI), which include five attributes: rock type, soil, slope, erosion type plus severity, and vegetation (Lynn et al., 2009, p. 12). The NZLRI has been digitised within the last two decades and can be accessed online by the public at the Land Resource Information Systems (LRIS) Portal (see Landcare Research, 2012). This information can be used for a variety of decision making, planning, and research purposes. This study was particularly interested in the attribute of erosion severity, as it was used as the underlying data for MFE’s proposed ESC system. Section 2.3 will provide further context of this subject.

1.1.3 Land Use Capability (LUC)

New Zealand's land use capability (LUC) system uses the NZLRI to support an expert assessment of NZ's land capacity for sustained production (NZ MWD & NWASCO, 1979, p. 11). Lynn and others (2009, p. 8) define a LUC system as, "… an arrangement of different kinds of land according to those properties that determine its capacity for long-term sustained production. Capability is used in the sense of suitability for productive use or uses after taking into account the physical limitations of the land."

1.1.4 Erosion Susceptibility Classification (ESC)

Bloomberg and others (2011) developed two versions of an ESC system, a 3-tier and 4-tier classification system. MFE adopted the 4-tier system because it best fitted their policy framework (MFE, 2011c). Bloomberg et al. (2011, pp. 12-13) provide a description of how the ESC was calculated in their report *Erosion Susceptibility Classification and Analysis of Erosion Risk for Plantation Forestry*, downloadable from:

http://www.mfe.govt.nz/laws/standards/forestry/erosion-susceptibilityclassification.pdf.

The ESC system was derived from the surveyed potential erosion severity attributes within the NZLRI. Section 1.1.4 will provide further context to the ESC system, which will be used to justify the need for plantation forestry activities to have a consent under the Resource Management Act 1991 (RMA) (MFE, 2012b).

1.2 Scope and Objectives

The primary focus of this study was to investigate the uncertainty in MFE's proposed ESC system resulting from the map scale of its underlying data (i.e., the LUC system). Work such as Kershaw (1957) and O'Neill et al. (1986) have shown that in natural sciences, natural scales occur within ecological processes and physical characteristics within a given spatial extent. Research suggests that the scale of a study determines the range of patterns and process that can be detected, thus an appropriate level of resolution for a study of these natural processes must be identified (Dark & Bram, 2007; Longley, 2001). Empirical judgement is used in designating areal map units, which define spatial extent of erosion severity measurements in LUC surveying. Hence it is imperative to understand the sensitivity of LUC measurements to different map scales. This need is easily observed when overlaying finer resolution LUC data (Todd, LandVision, Mulcock, & Taylor, 2012) with the original coarser data of the national LUC system (Landcare Research, 2000a), as illustrated in the heterogeneity of map units pictured in Figure 1.1. This figure illustrates that LUC map units surveyed at smaller map scales (finer spatial resolutions) are quite often different than the larger map scale (coarser resolution) National LUC map units when the two datasets are overlaid. This becomes a distinct problem when the map units are distinctly different, as seen in Figure 1.1 with the 7e3 (high erosion severity) Horizon LUC map unit, which is spatially located within a 3e5 (low erosion severity) NZLRI LUC map unit or the multiple lower Horizon LUC map units seen in the 8e3 + 3e5 NZLRI LUC polygon.

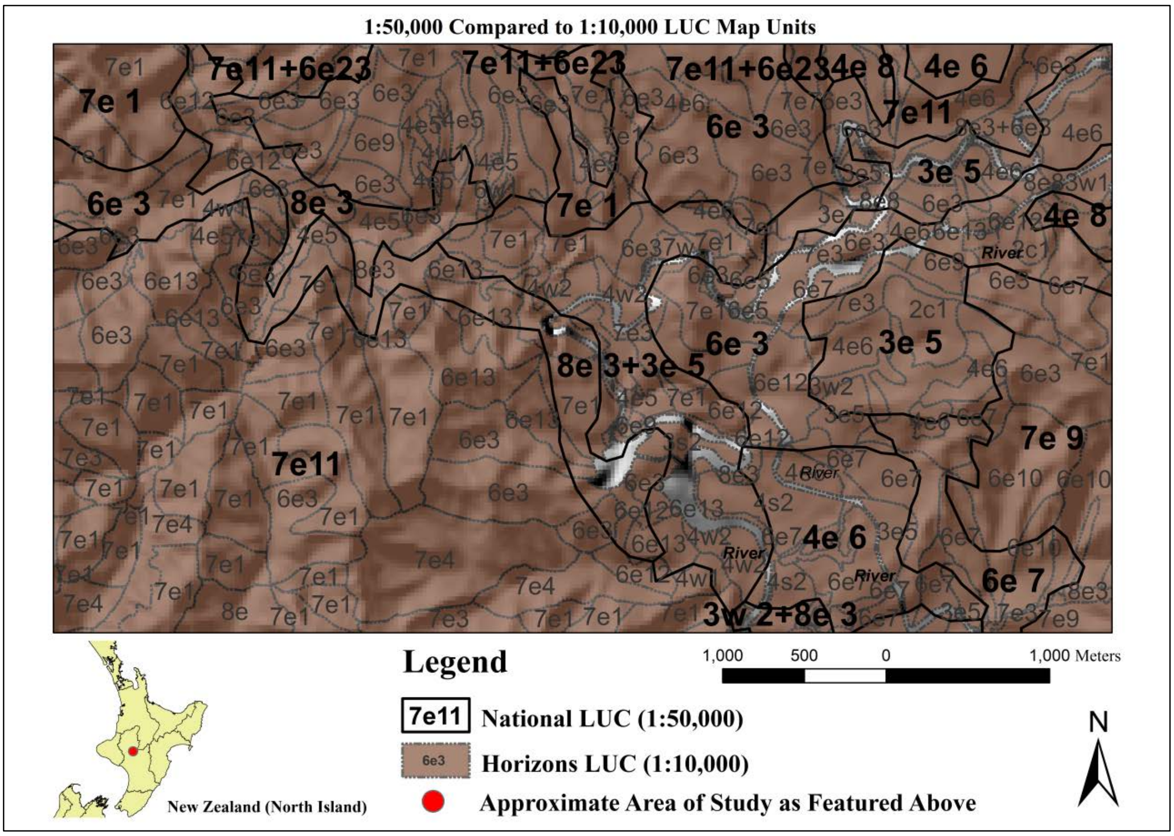

Figure 1.1: An initial assessment of homogeneity for sampled LUC map units, which compared the national NZLRI LUC survey to the Horizons LUC survey.

Bloomberg et al. (2011, p. 44) stated that "in order to account for important variations in erosion susceptibility at a site level, planning and regulation at a scale 1:5,000 to 1:10,000 is required." The ESC system which MFE adopted was derived from empirical erosion severity measurements that were measured at a fixed map scale of 1:50,000 or 1:63,360, thus the ESC system is only useful at roughly the same spatial resolutions. Furthermore, multiple variables, each measured at various scales were used during the measurement and development of the erosion values, from which the ESC is derived (Lynn et al., 2009; NZ MWD & NWASCO, 1979). The latter is a concern that is known as a Change of Support Problem (COSP), specifically an issue inherent with spatial data transformations (e.g., Arbia, 1986; Emery, 2008; Gelfand, Zhu, & Carlin, 2001; Gotway & Young, 2002). This happens when the spatial process of interest (i.e., erosion) is at one scale/form, while the datum observed is at another scale

(Arbia, 1986) or when a process occurs over a continuum (e.g., geological or meteorological process) yet point observations can be recorded and used for analysis (Gotway & Young, 2002).

1.2.1 Modifiable Areal Unit Problem (MAUP)

While the previous paragraph states an inherent and important problem with the underlying data of MFE's chosen ESC system, the following research will look at two interrelated issues of the Modifiable Areal Unit Problem (MAUP), a specific type of COSP (Gotway & Young, 2002), defined as "a problem arising from the imposition of artificial units of spatial reporting on continuous geographical phenomenon resulting in the generation of artificial spatial patterns" (Heywood, 1998). The two MAUP issues which were present in the ESC's underlying data and affect the perceived outcomes of the proposed ESC system are:

1. The "scale effect," which arises when deriving different inferences from the same data that has been spatially grouped into increasingly larger areal units (Gotway & Young, 2002; Openshaw, 1984b).
2. The "zoning effect," which is seen in the variability of the results due to alternative formations of the areal units leading to differences in unit shape (Gotway & Young, 2002; Openshaw, 1984b).

These problems occur when trying to use the ESC as a measurement of local level erosion severity, when the data are mapped and described at a regional level. King (1997) defines this situation as an "ecological fallacy," a special case of the MAUP, where aggregated data is used to make inferences about point locations.

When the ESC system was sent to end users for assessment, there was much criticism of the mapped variables as compared to perceived reality of the spatial areas observed (Bloomberg, 2012). These problems severely impair the reliability of the proposed ESC system and render it impractical for use at farm/forest scale. Research suggests that 1:50,000 map scale is not an appropriate spatial resolution for on-site erosion management (Jessen, 1987; Lynn et al., 2009; Saunders & Glassey, 2007). Thus, the following research objectives were formulated to test the sensitivity to spatial resolution of LUC areal map units and their erosion severity measurements.

1.2.2 Research Objectives

This research will provide a sensitivity analysis of spatial uncertainty produced from scale-dependent areal units registered in the MFE's proposed ESC system. Spatial uncertainty is described as a measure of error or spatial imperfections (Longley, 2001, p. 124), arising from the MAUP in the context of this study. This research will:

1. Attempt to identify a unique discriminant parameter of erosion, which can be applied across all landscapes of NZ and be used as a model to assess the spatial uncertainty in MFE's proposed ESC system.

2. Quantify the scale-dependent uncertainty in the ESC system, through a Geographic Information System (GIS) pair-wise analysis of two finer resolution underlying datasets, against the coarser national NZLRI LUC dataset.

These objectives were accomplished through a pair-wise comparison using a GIS and nonparametric statistics of the 1:50,000 scale NZ national NZLRI LUC dataset (Landcare Research, 2000a, 2000b) and two regional datasets, that is, the Sherry Catchment LUC survey (Burton, 2010) and the Horizons LUC survey (Todd et al., 2012), which were measured at a 1:10,000 map scale. Quantifying the degree of uncertainty between LUC surveyed map units and their erosion severity measurements, surveyed at different map scales, will provide a better understanding of an appropriate scale at which to map erosion severity.

1.3 Constraints

This thesis is constrained by the temporal/legacy aspect of the data used herein. The usefulness of outdated data is very limited for most applications except for those studies related to history or temporal phenomena (Li, 2007). Deciding when to update data, how to track versions, identifying required data, and how to automate any processes for efficiency while mitigating error, and then disseminating the data to end users is a difficult and time consuming task for those who have this responsibility. All maps have error. Thus, this thesis used the most up-to-date data possible. This thesis does not attempt to measure the degree of COSP uncertainty, which was a manifestation of spatial transformation of GIS objects and attributes from analogue (paper) maps to a digitised format. However, the importance of this subject will be mentioned in Section 2.5.

1.4 Assumptions

This study assumed that there are no overlapping map units within the data observed. Each dataset used (a data map is provided in Table 3.2) was developed independently and went through a system of auditing procedures. Each dataset used protocols outlined in the *LUC Handbook* (Lynn et al., 2009; NZ MWD & SCRCC, 1971) for developing a LUC survey.

All GIS data used in this study, which includes all LUC surveys assessed, had the projection or was transformed into the New Zealand 1949 Datum, using the International 1924 Spheroid and the New Zealand Map Grid projected coordinate system, as well as the New Zealand 1949 Geographic Coordinate System.

Autocorrelation is assumed to be naturally present within the variables observed in this thesis. Autocorrelation simply means that nearby areas are more alike than areas further away. Autocorrelation will not be taken into account by the statistical tests used in this thesis, but the outcomes of the spatial analysis conducted in this thesis will provide an understanding of the nature of autocorrelation of the variables observed in this thesis. Understanding the sensitivity to the level of detail or spatial resolution of an observed variable is fundamental to understanding the strength and nature of autocorrelation (Longley, 2001).

1.5 Thesis Strategy

The following sections outline the structure of the thesis and describe how each chapter will be used to help complete the research objectives. Two case studies were conducted in this study and the combined outcomes will be used as evidence to achieve the thesis objectives.

1.5.1 Chapter 2: Literature Review

This chapter expands upon the topics introduced in Chapter 1 which included erosion, the NZLRI, NZ LUC mapping and the ESC system. Erosion will be discussed so as to give a brief understanding of debris-flows and erosion related to plantation forestry, as this is more specific to the rationale of MFE's proposed ESC system and the intent of this study. A brief overview of NZ's erosion management policy will also be covered, to provide further context of the rationale for the development of an ESC system. Chapter 2 then reviews the MAUP and methodologies to quantify its presence, that is, thematic map comparison methods. This chapter ends with a section covering two research questions, which were used to investigate the level of agreement between LUC surveys at two different map scales.

1.5.2 Chapter 3: Methodology

This chapter provides the location and description of the two case studies investigated in this thesis, the Sherry River Catchment Case Study and the Horizons Case Study.

This chapter sets the framework for investigating the research questions stated in Section 2.8.1. It outlines a common methodology used in the two case studies presented in this thesis. Methods specific to each case study are covered in Chapters 4 and 5.

1.5.3 Chapter 4: Results - Sherry River Catchment Case Study

This chapter covers the results of a case study conducted in the Sherry River catchment of the Tasman Region, NZ. This case study had two aims, both focused on completing the thesis objectives; the first being, to examine the feasibility of using the Melton ratio, a known erosion discriminating parameter (Irvine, 2011; Watts & Cox, 2010; Welsh & Davies, 2011) as an independent variable to compare with erosion severity from LUC maps at 1:50,000 scale and 1:10,000 scale. Secondly, to quantify the degree of agreement between erosion severity values for LUC units measured in the Sherry River catchment (1:10,000 map scale), as compared to erosion severity values for LUC units of the national NZLRI LUC survey (1:50,000 map scale) (Landcare Research, 2000b) of the South Island, NZ. The quantified agreement is an indicator of sensitivity of spatial resolution used in LUC map development. This chapter uses GIS spatial analysis and nonparametric statistics to investigate the research questions stated in Section 2.8.1. GIS debris-flow modelling will be explained in the context of this study in Section 2.2.

1.5.4 Chapter 5: Results - Horizons Regional Case Study

This chapter focuses on a case study that looked at five areas (Areas of Interest A-E) within the Manawatu-Wanganui Region, NZ. This region's natural resources are managed by the Horizons Regional Council and have been independently surveyed at a 1:10,000 map scale.

Chapter 5 quantifies spatial resolution sensitivity by comparing (i.e. through an accuracy assessment) the Horizons LUC survey (sample map) (Todd et al., 2012), to the NZLRI LUC survey (reference map) (Landcare Research, 2000a); thus, providing a measure of uncertainty derived from aggregation and scaling effects and furthering the thesis objectives.

1.5.5 Chapter 6: Discussion

This chapter brings together and provides an interpretation and discussion of the results of the case studies presented in Chapter 4 and Chapter 5, in order to provide evidence to support the thesis objectives. Implications of the results chapters are also discussed, as well as limitations.

1.5.6 Chapter 7: Summary and Conclusions

Chapter 7 provides a summary of findings and suggests future research in erosion severity mapping and erosion management decision making.

Chapter 2 Literature Review

2.1 Introduction

This chapter provides further background and review of the literature related to the topics involved in this thesis. Erosion and in particular debris-flows are discussed in the context of plantation forestry. A review of erosion surveying is provided and the LUC system is further clarified. An understanding of NZ's current erosion management policy, which led to the development of MFE's ESC system, is given. This is followed by further exploration of the MAUP and a brief review of methodologies for quantifying spatial uncertainty. This chapter ends with a summary and states the research problem, which includes the research questions used to examine and complete the thesis objectives.

2.2 Soil Erosion

Anthropogenic erosion, frequently referred to as accelerated erosion, often originates from human alteration of the landscape, which may be already erosion-prone due to its inherent rock and soil composition. Some plantation forestry operations (e.g., road and platform cutting, tilling, and log harvesting) are preparatory factors for accelerated erosion.

Landcare Research classifies erosion into four types: surface, mass movement, fluvial, and depositional as seen in Table 2.1. Further descriptions of these erosion types can be found in the *Land Use Capability (LUC) Handbook* (Lynn et al., 2009). Eyles' (1983) analysis of the NZLRI concludes that surface erosion is the most extensive erosion type in NZ, with 75% of the South Island and 24% of the North Island being covered by surface erosion. Plantation forestry operations tend to primarily induce localised surface erosion (Eyles, 1983). Eyles further states that mass movement, most notably erosion types such as earthflow and debris-flows, are a significant issue in NZ. These erosion types cause serious property destruction and in many cases human fatalities (Saunders & Glassey, 2007). Both earthflow and debris-flow erosion types are more prominent in the North Island due to a large proportion of erosion-prone rock types being abundant in the landscape. All erosion types can be found in plantation forests at various degrees of severity.

Table 2.1: New Zealand Erosion Categories and Types.

Category	*Erosion Type*
Surface erosion	Sheet
	Wind
	Scree
Mass movement	Soil slip
	Earthflow
	Slump
	Rock fall
	Debris avalanche
	Debris flow
Fluvial erosion	Rill
	Gully
	Tunnel gully
	Stream bank
Deposition	Deposition

(Adapted from Lynn et al., 2009, p. 22)

Debris-flows are seen in all regions with sheer relief, even with occasional rainfall patterns (Jakob & Hungr, 2005, p. 1). This type of erosion was targeted in this thesis, in the attempt to identify an independent variable to test erosion severity predicted from LUC surveys. Often debris-flows are described as a form of mass movement where a saturated mass of soil, sediment, and rock debris flow down slope with similar properties as water (Lorenzini & Mazza, 2004, p. 194). Organic and anthropogenic debris, up to 60% by volume in forested steep lands are deposited as the debris-flow travels down slope (Hungr, 2005, p. 10). Sidle

(2005) provides a well-researched paper on the influence of forest harvesting activities on debris-flows. Most often debris-flows are triggered by geological, morphological, physical, or anthropogenic means (Wieczorek, 1996, p. 76). A trigger is defined by some external force, for example, rainfall (e.g., Hirano, 1997), earthquakes (e.g., You, Liu, Chen, & Pan, 2012), or volcanism (e.g., Scott, Macias, Naranjo, Rodriguez, & McGeehin, 2001). In some cases chemical or physical weathering of materials has been known to trigger debris-flows (Wieczorek, 1996, p. 76).

A GIS is often used for calculating geomorphic parameters such as drainage area, debris-flow lengths, and gully gradients (e.g. Jinn-Chyi, Ching-Weei, & Lung-Chang, 2009). This study looked at the GIS-rendered geomorphic parameter known as the Melton ratio (R). Originally postulated by Melton (1957), the Melton ratio is an empirical equation used to understand a watershed basin's ruggedness (Melton, 1965; Welsh & Davies, 2011), (Equation 2.1).

$$R = H_b / \sqrt{A_b} \qquad (2.1)$$

where H_b= the maximum elevation – the minimum elevation, known as the basin relief and A_b= the area of the basin. Wilford et al. (2004) used a GIS to help statistically model and test the Melton ratio along with watershed length, relief ratio (Costa, 1988), and a proportion of a watershed with a slope gradient between 30-40º called B3040, to determine the best parameters for identifying debris-flow prone watersheds in British Columbia, Canada. Their model correctly identified 92% of debris-flows within 65 AOIs, using the parameters of Melton ratio and watershed length. Welsh and Davies (2011) adapted their findings to a NZ context and found that Melton ratio and watershed length were reliable for identifying debris-flow catchments in NZ's mountainous environment.

Irvine (2011) investigated the thresholds of the Melton ratio and the potential for debris-flow modelling. His report looked at a non-GIS derived model (Watts & Cox, 2010), the Welsh model (Welsh, 2008), and a River Environmental Classification (REC) debris-flow model (Irvine, 2011). The latter was chosen for this case study and will be elaborated on in the Section 3.5. Irvine (2011) believed the REC debris-flow model was the best choice given the readily available REC ordered polygons (NIWA Research Ltd., 2009) and marginal variance in Melton ratios between all models he assessed, which are listed in Table 2.2. However, the REC debris-flow model had issues with catchment definition and stream placement, as well as lake definition.

Table 2.2: Melton Ratio Thresholds by Study and Location.

Study and Location	*Melton's R Threshold*
Welsh and Davies, 2010 – Coromandel, NZ	0.5
Watts and Cox, 2010 – Otago, NZ	0.4
De Scally et al, 2010 – Southern Alps, NZ	0.45
De Scally and Owens, 2004 – Southern Alps, NZ	0.75
De Scally et al, 2001 – Cascade Mountains, British Columbia	0.38
Jackson et al, 1987 – Rocky Mountains, Canada	0.6

(Adapted from Irvine, 2011)

2.3 Erosion Surveying

Erosion became a problem in the 1930s in NZ (Eyles, 1983), and even after the creation of the Soil Survey Division in 1935, a branch of Department of Scientific and Industrial Research (DSIR), erosion was not specifically focused on until 1938 (Cumberland, 1944, p. 7). On the 29th September 1941, after a public outcry and news from the US on similar issues (i.e., the great Dust Bowl), Parliament took action by ratifying the "Soil Conservation and Rivers Control Act 1941." This Act authorised the creation of Catchment Boards under the authority of a Soil Conservation and Rivers Control Council (SCRCC) (Cumberland, 1944). According to Part 7, Section 126(1), each Catchment Board would have the function and powers to "…minimise and prevent damage within its district by floods and erosion" (Parliamentary Counsel Office, 2008, p. 83).

To understand the magnitude of erosion in NZ, multiple surveys were conducted looking specifically at soil erosion. In 1944, SCRCC's Kenneth B. Cumberland wrote a book entitled *Soil Erosion in New Zealand: a geographic reconnaissance* to further explain to the public the seriousness of erosion. The earliest scientific soil survey was conducted by Gibbs et al. in 1945 (as cited in Eyles, 1983). The intention of this survey was to understand erosion, which was believed to be derived from the over-burning of the tall tussock lands of Central Otago and the subsequent infestation of rabbits (Gibbs, Raeside, Dixon, & Metson, 1945). These two factors affected the utilisation of the high country for the production of wool (Gibbs et al., 1945, p. 5), thus justifying the survey economically. Grange and Gibbs (1947) planned to complete a nationwide erosion survey, but only part of the North Island mapping was published. This survey mapped soil by its susceptibility to erosion and intended to map distinct erosion types.

By 1970, 40% of NZ's rock type, slope, vegetation, soil, and erosion severity had been inventoried and mapped by the Ministry of Works and catchment authorities (Eyles, 1983). SCRCC finally decided to complete a nationwide survey of NZ for the purpose of assisting the National Water and Soil Conservation Organisation (NWASCO) (NZ MWD & NWASCO, 1979, p. 9). Ministry of Works officers surveyed NZ with the intention of classifying land according to its capability for permanent sustained land production (NZ MWD & SCRCC, 1969, p. 11). In 1969, the first edition of the *LUC Handbook* was published by SCRCC with the purpose of unifying procedures for NZ LUC mapping (Lynn et al., 2009, p. 3). The preface of the *LUC Handbook* states that this book was:

"…based on the U.S.D.A. [United States Department of Agriculture] Miscellaneous Publication No. 352 "Soil Conservation Survey Handbook" by E.A. Norton, 1939. The U.S.D.A. Agriculture Handbook No. 61 "A Manual on Conservation of Soil and Water", 1954, and U.S.D.A. Agriculture Handbook No. 210 "Land Capability Classification" by A.A. Klingebiel and P.H. Montgomery, 1961— although slightly modified as necessary for better application on New Zealand's dominantly hilly landscapes with their predominance of grassland farming for the production of meat and wool."(p. 5)

The *LUC Handbook* (1969) and its subsequent editions in 1971 (NZ MWD & SCRCC) and 2009 (Lynn et al.), outlined the methods for collecting variables essential to compile the NZLRI.

2.3.1 NZ's Land Use Capability System

As described in the previous section, a land resource inventory (LRI) is the dataset needed to classify LUC management areas in NZ. LUC mapping was first used in NZ for planning sustainable land development and management of individual farms/run plans in 1952 (Lynn et al., 2009, p. 7) and was also fully adopted as a management tool for soil conservation by SCRCC (Eyles, 1985, p. 4). Later, catchment authorities decided to use the LUC system for other complex regional issues (MWD & NWASCO, 1979, p. 9). The Ministry of Works from 1975–1988 developed the NZLRI system to account for all LUC units mapped in NZ. By the late 1970s, 89,873 map units had been identified and mapped. Today, there are 100,000 mapped units (Landcare Research, 2012). Upon the disbanding and privatisation of the Ministry of Works in 1988, a former branch of the DSIR known as Landcare Research became the custodians of the NZLRI. Figure 2.1 is an example of the first edition LUC analogue map. An example of the map's symbology is shown in Figure 2.2.

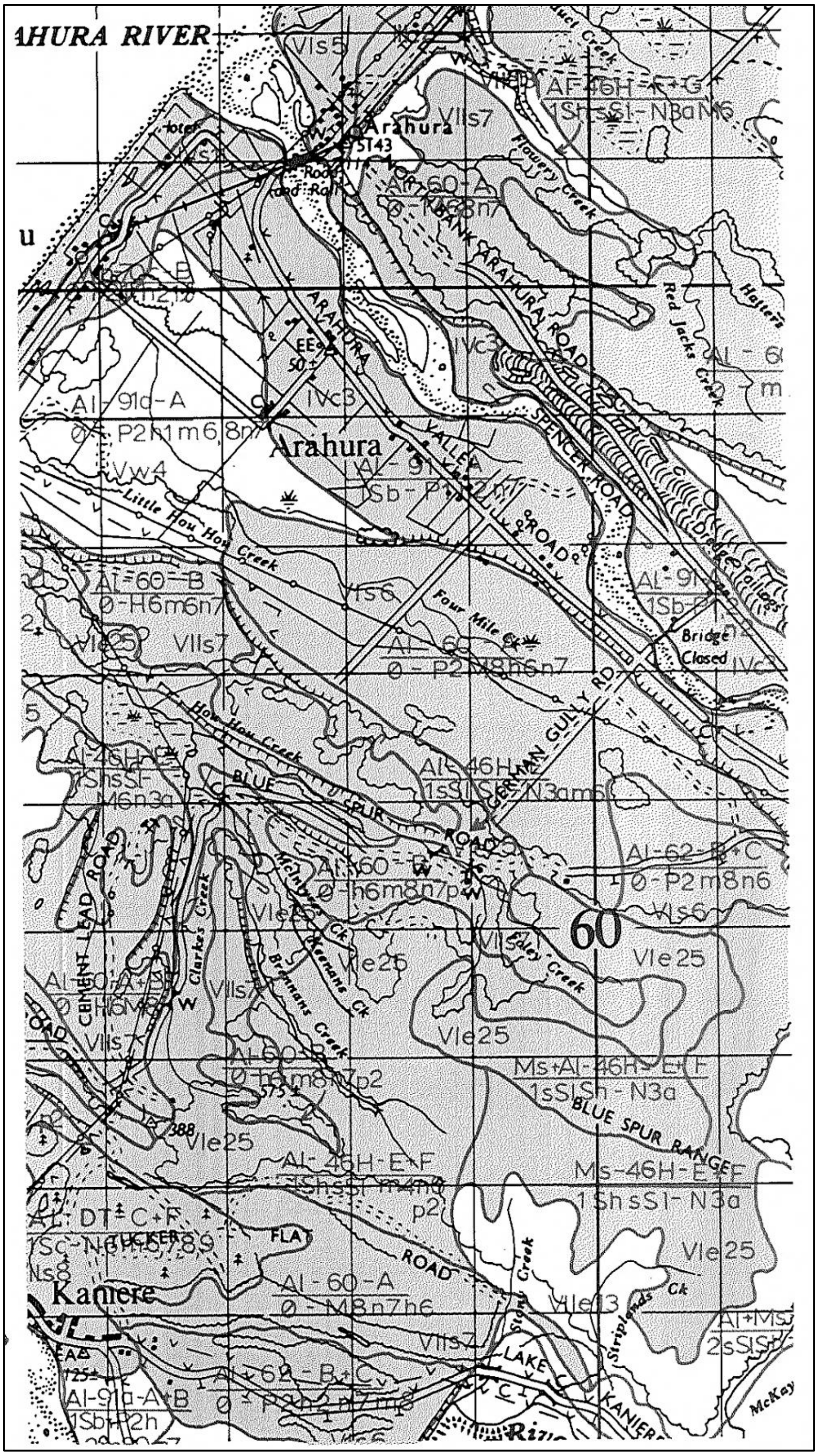

Figure 2.1: Example of an analogue LUC map.

(From NZ MWD and NWASCO 1979, p. 67)

$$\frac{Rock - Soil - Slope}{Erosion\ degree\ and\ type - Vegetation}$$

Example: $\frac{\text{Gw}-124-\text{F}}{1\text{sSI}-\text{PIMI}}$

Gw	=	Graywacke (indurated sandstone)
124	=	Ruahine stony silt loam
F	=	Slopes between 25° and 35°
1sSI	=	Slight soil slip erosion (edition 2 code =1Ss)
PIMI	=	Improved pasture with manuka scrub

Figure 2.2: An example of the coding system from the NZLRI.
(Reproduced from Landcare Research, 2012)

A LUC map unit is developed by inventorying the land attributes used for analyses of a large range of geographical, agricultural, and scientific questions. As mentioned in the introduction, the NZLRI consists of five physically mapped factors, which include rock type, slope angle, erosion type including severity, and vegetation cover (Lynn et al., 2009, p. 14). Geomorphologists and other specialists first use aerial photography (stereo pairs) to outline polygons based on major landform boundaries. The newly formed polygons are “modifiable areal units” and are the basis of the MAUP (Modifiable Areal Unit Problem) studied in this thesis. Polygons are depicted on worksheets at a specified map scale (usually 1:5,000 to 1:50,000). For each polygon, a land resource inventory (LRI) is then conducted. The five previously mentioned physical land characteristics are either described using classification systems or quantified using ordinal scales, by empirical field observation. Empirically assessed values are generalised, that is, assumed to apply for the entire area contained within the map polygon to which they are applied.

Using the LRI, each polygon is then classified into a land use capability class, based on its constraints to productive use (Table 2.3).

Table 2.3: LUC Classification Code Descriptions.

↓ Increasing limitations to use ↓

↓ Decreasing versatility of use ↓

LUC Class	Arable cropping suitability	Pastoral grazing suitability	Production forestry suitability	General suitability
1	High	High	High	Multiple use land
2				
3				
4	Low			
5	Unsuitable			Pastoral or forestry land
6				
7		Low	Low	
8		Unsuitable	Unsuitable	Conservation land

(Reproduced from Figure 2 of Lynn et al., 2009, p. 9)

Within a particular LUC class, polygons are then further classified into sub-classes based on which of the four common limitations to productive use is dominant (i.e. erosion (e), soil (s), wetness (w) or climate (c)). Finally, within each erosion class and subclass, polygons will be assigned to an LUC unit, where it is grouped with other polygons with similar management and conservation requirements (Figure 2.3).

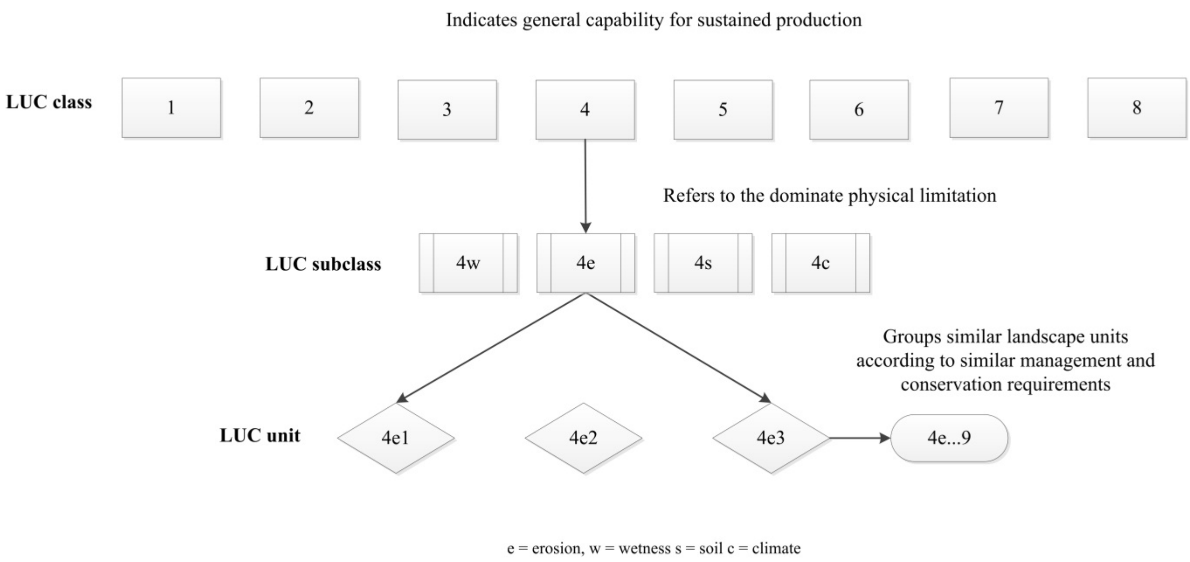

Figure 2.3: LUC class example and hierarchal structure.
(Reproduced from Lynn et al., 2009, p. 8)

NZ's LUC class system has a few assumptions as explained by Lynn et al. (2009, p. 85):

1. Permanent physical limitations of the land remain.
2. Rectifiable limitations may be removed.
3. An above-average level of land management is practised.
4. Appropriate soil conservation measures will be applied and maintained.

Further insight into the development of the NZLRI and NZ's LUC system can be found in the *LUC Handbook* (Lynn et al., 2009) and on Landcare Research's website (see Landcare Research, 2012). NZ's LUC system is an interpretation of the data derived from the NZLRI. NZ's LUC map units and other natural resources data can be viewed and downloaded from the Landcare LRIS Portal (see Landcare Research, 2010). The LUC system in its digital form separates each NZLRI attribute into an independent attribute field and is stored in a geospatial format for spatial analysis.

2.3.2 NZ's Proposed Erosion Susceptibility Classification (ESC)

Bloomberg and others (2011) developed an erosion susceptibility classification that uses the NZLRI erosion type and potential erosion severity attributes to estimate the intrinsic predisposition of land units to mass-movement and gully type erosion (Bloomberg et al., 2011, pp. 10-11). Table 2.4 provides the ESC classification and its associated potential erosion severity values. The ESC system is a tool which land managers can use to assess potential erosion throughout NZ, setting regulatory limitations to plantation forestry. The maximum erosion severity, based on mass-movement and gully type erosions, was parsed from each LUC map unit and calculated into a new attribute field representing each polygon's maximum erosion severity (Named: PolyMaxSev). This field has categories that range from 0-5 and are listed in Potential Erosion Severity column in Table 2.4. The underlying data used to produce the ESC (i.e., the PolyMaxSev attribute field) was used in this case study to assess erosion severity.

Table 2.4: Erosion Susceptibility Classification System (ESC).

<table>
<tr><th>Potential Erosion Severity</th><th>ESC Class</th></tr>
<tr><td>0 = Negligible</td><td rowspan="2">Green</td></tr>
<tr><td>1 = Slight</td></tr>
<tr><td>2 = Moderate</td><td>Yellow</td></tr>
<tr><td>3 = Severe</td><td>Orange</td></tr>
<tr><td>4 = Very Severe</td><td rowspan="2">Red</td></tr>
<tr><td>5 = Extreme</td></tr>
</table>

2.4 Current Erosion Management Policy in New Zealand

The Resource Management Act 1991 (RMA) is the current legislation underpinning erosion management policy in NZ. It attempts to integrate management of air, land, fresh water, and marine areas into one piece of legislation (Peart, 2008, p. 15). The RMA is an effects-based rather than an regulatory/prescriptive planning system as seen in the Town and

County Planning Act 1977 (Peart, 2008, p. 15). The RMA mediates activities that are likely to result in unacceptable environmental impacts (e.g., substantial erosion stemming from plantation forestry practices). Part 4 of the RMA outlines the functions, powers, and duties of central and local governments (Parliamentary Counsel Office, 1991). This thesis is tied to Part 4A, which provides for National Environmental Standards (NES) and defines standards for erosion management in plantation forestry. Section 43(1) of the RMA outlines the issues which NESs address, this includes: use of land, subdivisions, use of coastal marine area, use of beds of lakes and rivers, water, discharges of air, land, and water, noise, and monitoring. Section 43(2) of the RMA outlines the content of an NES which include: qualitative or quantitative standards; discharge standards; methods for classifying a resource; methods, processes or technologies to implement standards; and exemptions from standards.

Currently each region or territorial authority manages plantation forestry erosion under a Land and Vegetation Management plan (e.g., Canterbury Regional Council, 1997) or plantation forestry, waterway, and/or erosion guideline (e.g., Hawke's Bay Regional Council, 2009). As mentioned in the introduction, a NES for plantation forestry is currently under review. The intent of this NES was to improve national consistency in local authority plan rules relating to plantation forestry and provide a framework to help in management and planning for invested interests in plantation forestry (MFE, 2012b). According to the MFE (2012b), the proposed NES:

- "Covers the activity status and conditions that might apply to eight plantation forestry activities (afforestation, replanting, mechanical land preparation, harvesting, pruning and thinning to waste, earthworks, quarrying and river crossings)."
- "Does not cover some associated forestry activities (e.g. agrichemical use, milling, and processing of timber)."

- "Allows local authorities to retain control over how local natural and physical resources are managed in some circumstances."
- "Proposes an erosion susceptibility classification system for determining the activity status for some plantation forestry activities."

A key component of the NES for Plantation Forestry is an erosion susceptibility classification (ESC) system, used for identifying land where forestry activities would be permitted or require a resource consent (MFE, 2012b). It is the underlying data of this ESC system (2011) which has been accepted in the proposed NES for Plantation Forestry, from which this thesis derives its research question. If the scale of observation influences the outcome of analyses (Cocklin, Blunden, & Moran, 1997), then is the scale of the ESC system (i.e., 1:50,000) the proper map scale for its intended purpose of farm/forest level erosion management?

2.5 Cartography of the ESC's Underlying Data

A map is a spatial representation of reality, used as a visual communications platform, providing information about spatial and semantic characteristics of the natural world and cultural phenomena (Li, 2007, p. 1). In general there are three types of maps: topographic, thematic, and special maps; the latter having characteristics of both a topographic and thematic map (e.g., visitor maps of a museum). Thematic maps represent a theme of natural or cultural phenomena. The product of a LUC survey, whether analogue or digital, is a thematic map with a defined symbological structure and hierarchy as previously described.

A thematic transformation, which this thesis investigated, involves the changing of the meaning or hierarchy of the map, possibly including the map scale (Li, 2007, p. 17). The scale or level of resolution of a map often determines what spatial or temporal detail will appear normal or not (Longley, 2001, p. 98). This issue is expressed in the *LUC Handbook* (Lynn et al., 2009) when choosing the appropriate scale for a survey, as illustrated in Figure 2.4. Jones (1997, p. 271) explains that "a major constraint to the information content of a map is scale, in so far as it dictates the space available for symbols." As explained in the Chapter 1, map scale is defined as the ratio between a measured distance on a map and the real world distance which the measurement represents (Jones, 1997, p. 123). For example, any line on a 1:10,000 scale map which is 0.5 mm in width (the width of a standard mechanical pencil point) corresponds to a ground distance of 5 m in reality. This problem is the beginning of mapped error or more specifically the introduction of spatial uncertainty caused by generalisation. Approximately 5 m of represented reality is lost on a map when attempting to record an attribute using a 0.5 mm line as its symbol. This thesis attempts to understand spatial uncertainty from the empirical generalisations made during the resource inventory process. This thesis does not attempt to measure the uncertainty as a product of digitisation. This thesis quantifies the uncertainty induced by surveyors who empirically derived areal units, based on a system of generalising the spatial extent of erosion severity associated with slope, and slope face, lithology, soil, climate, and morphological attributes of an areal extent of land, at different map scales.

Scale level[1]	National	Regional	District and catchment	Farm
Scale[2]	1:250,000 to 1:100,000	1:100,000 to 1:50,000	1:50,000 to 1:15,000	1:<15,000
Scale size[3]	Small ⟵		⟶	Large
Map detail[3]	General ⟵		⟶	Detailed
Smallest area[4]	40–250 ha	10–40 ha	1–10 ha	≤ 1 ha
LUC level	Dominant capability class or subclass	LUC unit (regional)	LUC unit (regional)	LUC unit (regional and farm[5])
Common application examples	Strategic overview, broad planning, prioritising or targeting projects for detailed investigations.	Land use planning, targeting of regional priorities and projects, reference for more detailed survey.	Catchment projects, small district/community projects, farm planning for large properties.	Farm planning (detailed), nutrient budgeting, farm development projects, precision agriculture.

[1] Scale levels are subjective. Meaning is often dependent on context (e.g. a 'detailed' scale in a farming context is different from a 'detailed' scale in a regional context).
[2] Recommendations are based on common NZ scales used in soil, geology and LRI/LUC surveys.
[3] Large and small scale terminology is confusing. A 'large' scale (e.g. 1:5,000) is actually more detailed than a 'small' scale (e.g. 1:500,000). Scales are essentially fractions, and fractions with large denominators are smaller numbers (e.g. 1:5,000 is the same as 1/5000 or 0.0002, which is a larger number than 1:500,000 = 0.000002).
[4] The smallest area of interest represents the minimum legible area (MLA) that can be displayed on a paper map at a given scale. Any smaller and labelling becomes illegible, and line boundaries become disproportionate. Modern digital printing can accommodate a minimum legible area as small as 0.4 cm^2 (after Forbes *et al.* 1982).
[5] Occasionally regional LUC Units may require adaptation at the farm scale (see Section 4.4).

Figure 2.4: Table from the *LUC Handbook* for selecting the appropriate scales for extensive LUC surveys. The "Smallest area" Scale Level is analogous to spatial resolution.

(From Lynn et al., 2009, p. 100)

Generalisation is the process of abstraction. This development is a common issue for different types of spatial representation (i.e., different map scales, resolutions, and management levels) and is also present during the modelling of the spatial process (e.g., erosion susceptibility) (Li, 2007, p. 9). Jones (1997, p. 271) explains that there are two types of generalisations:

1. Semantic generalisation, which involves selecting the relevant information for a geographical database or map. It implies powers of abstraction that depend upon geographical concepts, most notably a hierarchical structure which provides the meaning and function of a map or GIS database. This structure is visualised through the use of symbology. In the context of LUC surveying, this generalisation is illustrated in Figure 2.3, as well as Table 2.3, where the symbology and hierarchical structure of the LUC system is explained.

2. Geometric generalisation, which arises from sematic generalisation, symbolisation, and the constraints of map scale. It is the process of increasing the level of graphic abstraction relative to the original surveyed form of spatial phenomena. This thesis will quantify this form of generalisation in Chapters 4 and 5. They compare two different empirical generalisations of derived areal LUC map units and perceived erosion severity measurements, spatial resolution being the limiting factor.

While the geometric generalisation in this thesis was empirically driven, there are cartographic models that attempt to minimise uncertainty during the mapping process. Shea and McMaster (1989) provide a good summary on why and how we generalise spatial content for user operations. There are two changes of spatial representations or mapped objects, which are distinguished by user operations on a map; the first being generalisation resulting from a zoom out, illustrating a decrease in detail and the second being refinement from zooming in or an increase of detail (Follin, Bouju, Bertrand, & Boursier, 2005). According to Follin et al. (2005) and Bertolotto and Egenhofer (2001) there are three categories of operators:

1. Metric operators: “Handling changes related to simplifications and decreases in size, i.e. affecting the shape of objects.”
2. Topological operators: “Handling changes in dimension and complexity of objects.”
3. Semantic operators: “Handling changes related to attributes.”

Figure 2.5 illustrates metric and topological operators in relation to mapped objects. For a list of the majority of current algorithms available for user operators, see Li (2007, p. 11).

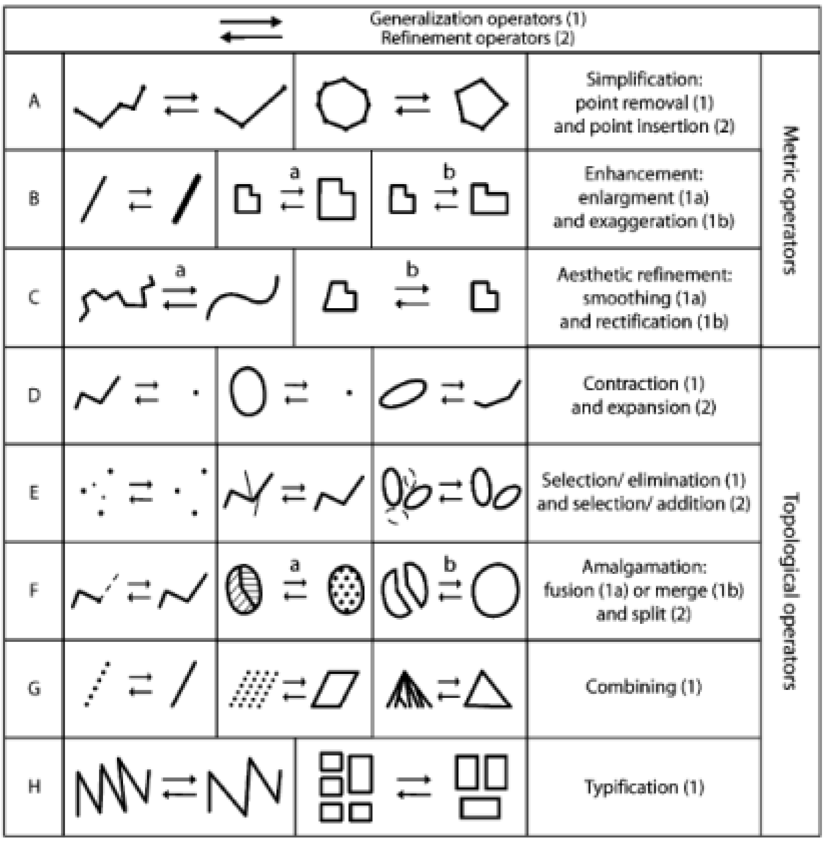

Figure 2.5: Generalisation and refinement operators in map transformations.
(From Follin et al., 2005)

2.6 Modifiable Areal Unit Problem

Most of what is known about the "scale problem" has come from research of social scientists on census data. Using census tract variables, Gehlke and Biehl (1934) were the first to state that a statistical inference could change with scale. They grouped 252 census tracts from Cleveland, USA into larger units and identified that the magnitude of the correlation coefficient increased when looking at juvenile delinquency and median monthly income using both absolute numbers and ratios. Gehlke and Biehl (1934) also concluded that when random census tracts were grouped, the correlations were unaffected by the group size. This implication was further studied by Yule and Kendall (1950), finding that when proximal census tracts or larger aggregated areal units were grouped, the estimations of both the correlation coefficient and the slope parameters of simple liner regression increased with the level of grouping. They showed how wheat and potato yields for the 48 counties of England increased; as spatial aggregation reduces the number of areal units and increase their size and scale of analysis. This is the foundation of Tobler's Law (Tobler, 1970) or "The first law of geography," which states that "everything is related to everything else, but near things are more related than distant things" (Longley, 2001, p. 99). Robinson (2009), originally published in 1950, concluded that at the time, all methods for looking at aggregated data as an inference of individual relationships were inadequate and thus should be avoided at all costs. His work was influential, causing social scientists and scholarly purists to end the use of aggregated data to infer individual relationships for some time (King, 1997, pp. 4-5). It was later realised, that in some cases aggregated data could be used if enough is known about the observed variables (e.g., Openshaw, 1984a).

The "scale problem" has been discussed in the literature since the 1930s (e.g., Gehlke & Biehl, 1934). It was not until the revolution of the microprocessor, GIS platforms, and Openshaw and Taylor (1979) defining the issue as the "Modifiable Areal Unit Problem," that a better understanding of the relationship of scale and areal units became a motivating research topic. As Openshaw (1984b) states, "The MAUP is in reality composed of two separate but closely related problems. The first of these is the well-known scale problem which is the variation in result that can often be obtained when data for one set of areal units are progressively aggregated into fewer and larger units for analysis." Openshaw continues with identifying the second sub-problem by saying that, "although scale differences are a most obvious manifestation of the MAUP there is also the problem of alternative combinations of areal units at equal or similar scales." The scale problem and grouping problem (i.e., sub-problems to the MAUP) are also known as the "scale effect" and "zoning effect". Gotway and Young (2002) provide an in-depth history and review of the MAUP. Openshaw (1984b) also provided a review of the MAUP with multiple examples from both a geographer's and statistician's point of view. Openshaw (1984b) concluded that the MAUP is a "geographical problem that is endemic to all studies of spatially aggregated data. It is a geographical fact of life that the results of spatial study will always depend on the areal units that are being studied." Therefore, the MAUP could be used as an analytical tool for probing the structure of areal datasets (Openshaw, 1984b, p. 38); exactly what this thesis intends to achieve.

This thesis used the MAUP as a tool for analysing the degree of thematic transformation, specifically the degree of uncertainty involved, when comparing empirically defined erosion severity spatial units at a local level (i.e., 1:10,000 map scale) to regional level (i.e., 1:50,000 map scale) LUC erosion severity measurements, derived using the same methods.

2.7 Uncertainty in the Areal Units of LUC Erosion Severity

As previously explained, the NZLRI is a dataset of five inventoried physical land variables, used in the development of a LUC survey. The NZLRI was measured at a 1:63,360/1:50,000 map scale according to the *Data Dictionary* that accompanies the NZLRI database (Newsome, Wilde, & Willoughby, 2008). The metadata for the NZLRI suggest the data is appropriate for presentation at 1:50,000 map scale and it will henceforth be denoted as such.

1:50,000 map scale can be appropriate for many national, district, and regional management issues (Lynn et al., 2009, pp. 11, 100), yet the question is whether this scale is appropriate for forestry related ESC management issues (see Landcare Research (2012) for examples of the use of the NZLRI at different management levels). Management decisions are influenced by map scale/spatial resolution, when there is a high variability within the mapped attributes. This can be seen in the variability of soil properties, including erosion, when viewed from different scales (Hennings, 2002). Thus, it is important to study erosion susceptibility at multiple scales with the intent of understanding which scale to use when making local, regional, and/or national management decisions. These decisions are made by people ranging from land planners who manage millions of hectares of land, to farmers who utilise fewer than 10 hectares. If the proposed NES for plantation forestry is ratified, stricter regulations will be placed on higher LUC classes; such as classes 7 and 8. Many districts, regional councils, and even forest companies have LUC units mapped at smaller map scales (≈ ≤ 1:35,000) (Lynn et al., 2009, p. 11), some of which are studied in the following chapters. However, this data has not gone through the same extensive verification and auditing process as the national standard NZLRI dataset, and was not used in deriving the ESC.

When LUC units are mapped at a coarse resolution, some map units will inevitably be merged, exemplifying the issues of the MAUP. An example of this was illustrated in the heterogeneity of LUC map units seen in Figure 1.1. This is due to the variability of the inventoried attributes needed to create NZ's LUC system and in some cases the use of natural and anthropogenic land features as map unit boundaries. The smallest unit of interest is also vital when choosing a map scale for management decisions.

2.7.1 Quantifying Uncertainty

It is easy to assume that comparing maps is a simple task, yet it is a complex undertaking (Hargrove, Hoffman, & Hessburg, 2006), which can involve many processes. Deciding how to compare two or more maps is often influenced by the type of map, objectives of analysis, and the desired perspective (Foody, 2007). Visser and de Nijs (2006) suggest four reasons for comparing maps: 1. To compare models under multiple methodologies or scenarios (e.g., Boots & Csillag, 2006); 2. To detect temporal/spatial changes (e.g.,Wilde, 1996); 3. To calibrate and validate land-use models (e.g., Kok, Farrow, Veldkamp, & Verburg, 2001; Loonen, Koomen, & Kuijpers-Linde, 2007); 4. To perform uncertainty and sensitivity analysis (e.g., Congalton & Green, 1999; Lucieer & Lamarche, 2011). This thesis used a GIS and the statistical platform R (R Core Team, 2012) to perform an uncertainty and sensitivity analysis between the erosion areal units previously described.

2.7.2 Geographical Information Systems

A Geographic Information System (GIS) will be used in this thesis to quantify the degree of uncertainty between two empirically-derived LUC maps with different spatial resolution (i.e., map scales) and areal units. A GIS comprises an information system (IS), which captures, stores, analyses, and displays geographically referenced information (Folger, 2011, p. 1). Chapter 3 will cover the design and methodology of the use of GIS in the pair-wise comparison of uncertainty between maps. There is a strong literature on the application of GIS to soil science (e.g., Landcare Research, 2011c) and physical geography. One of the major themes of the first widely read text book on GIS, *Principles of Geographic Information Systems for Land Resource Assessment* by P.A. Burrough (1986) was soil science (as cited by Jones, 1997, p. 10). With the explosion of new technology and consumer demand, GIS have become fundamental in many lives of people from all around the world. This ranges from Global Positioning Systems (GPS) linked to cell phones, Google Earth, and GIS web applications. See Jones (1997) for a good introduction and understanding of GIS and its applications.

The use of GIS in planning and decision making has become essential to keep up with exponential growth of populations and urbanization. In October of 2006 NZ’s ministerial cabinet agreed upon the development of the New Zealand Geospatial Strategy (Land Information New Zealand, 2012). The strategy was developed by Land Information New Zealand (LINZ) who reports to the New Zealand Geospatial Office (NZGO). The NZGO are responsible for coordinating the development of the work programs associated with the strategy, supporting initiatives, and other liaising between governmental agencies (Land Information New Zealand, 2012). In 2010, the Cabinet agreed to develop a national spatial data infrastructure for NZ, mandated by LINZ, through the NZGO (Williamson, 2010). Thus, GIS has become enshrined in NZ governmental policy and the NZ Cabinet has mandated the development of an interoperable GIS network as a strategic planning and decision making tool.

GIS use two data structures or models for analyses and development, raster and vector. Figure 2.6 graphically illustrates these models. Vector data consist of points, lines, and polygons that represent spatial area and often contain tabular data. Vector systems define an object by its X and Y coordinate location (with the option of a Z value), characteristics, and attributes (Morain & López Baros, 1996, p. 35). A raster system is a grid based system that is primarily concerned with an object's location. It then assigns a value (synonymous with an attribute) to a cell that is identified by a corresponding location (Morain & López Baros, 1996, pp. 35-36).

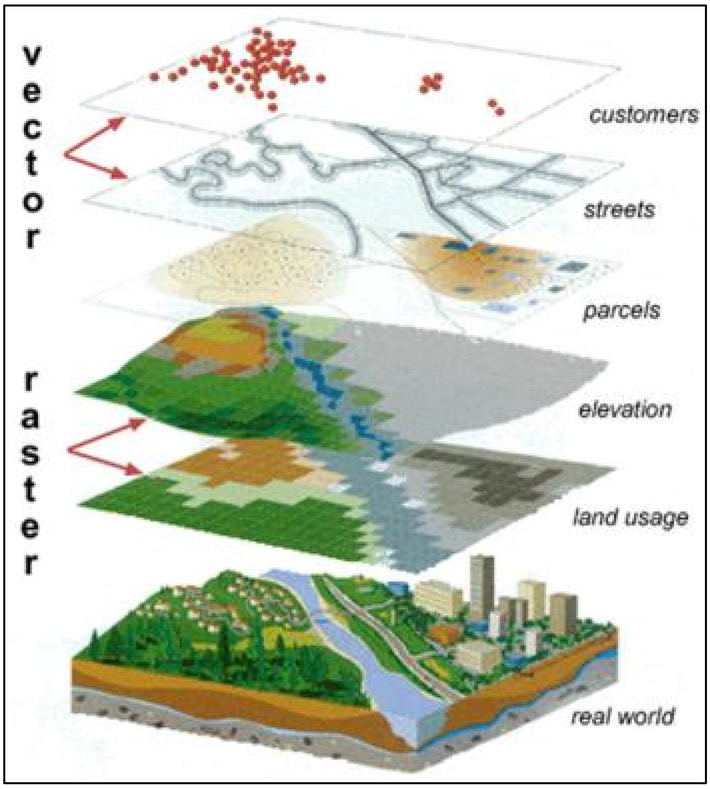

Figure 2.6: Illustration of vector and raster GIS models.
(Retrieved from: tangatawhenua.com)

2.7.3 Vector Modelled Map Comparison Analyses

Basayigit and Senol (2008) studied the variability of soil properties by comparing maps at different scales using a vector model. They compared two detailed paper soil survey maps at scales 1:200,000 and 1:25,000 of the same area in the Ceyhan Plain of Turkey, to a nationwide thematic reconnaissance paper soil map at 1:200,000 scale. Four test areas were selected. All test areas contained alluvial soils as the dominant soil type, which was the focal soil type of this study. All three soils maps were digitised into vector format and compared using GIS (Basayigit & Senol, 2008). As mentioned in the previous section vector data consists of points, lines, and polygons that represent spatial area and often contain tabular data. The authors reclassified some variables within the detailed map dataset, to have a comparable dataset to the reconnaissance soil map. For example, the units clay, sandy clay, and silty clay were dissolved into one variable called fine texture. Soil surveys often have scale limitations and/or inadequate quantitative data, forcing the union or exclusion of map units (Lin, Wheeler, Bell, & Wilding, 2005). The accuracy of the variables studied in the 1:200,000 reconnaissance soil map, when compared to the 1:25,000 detailed soil map were described by Basayigit & Senol (2008) in the following order respectively: slope, depth, salinity, texture, drainage, and topsoil texture. However, a confounding factor in this study was that 92% of the area had nearly level slope topography (Basayigit & Senol, 2008). Basayigit and Senol analysed the previously mentioned variables, using a GIS, by comparing the means of the mapped soil properties acquired from tabular data within the four sample areas' map units (polygons). This study's map units were defined by soil boundaries that were digitised to vector format from the original paper maps being compared. The calculated means represent the percent area of conformity for each mapped variable. The conformity ratios were compared between the reconnaissance soil map and the detailed soil map in the four test areas and tested for significance. An Analysis of Variance (ANOVA) was also performed on these variables. Basayigit and Senol concluded by suggesting that the aggregation of fine scale map units would improve 1:200,000 land quality maps (Basayigit & Senol, 2008).

Galli et al. (2008) compared three landslide inventory maps. They compared maps of the Umbria region of Italy, one being a reconnaissance map (1:100,000 scale) and the other a detailed geomorphological landslide map (1:10,000 scale). The third map was a multi-temporal landslide inventory map (1:10,000 scale) of the Collazzone area of Italy, which is in the centre of the Umbria region. Galli et al. (2008) performed three tests to compare landslide inventory maps:

1. A "pair-wise" comparison of the mapped landslides using GIS, with the goal of identifying the degree of cartographic match between the researched maps.
2. Comparison of the proportion of landslides in pre-defined land units between all three maps.
3. Comparison of the frequency-area statistics —acquired from different inventories— of landslides from each map to understand the variance of landslide susceptibility between all maps (point data).

Guzzetti et al. (2002) explain that the arithmetic mean may not be the best descriptive statistic to base quantitative spatial analysis in their study. Thus, Galli et al. used Carrara et al.'s (1992) equation to identify overall error (E):

$$E = \frac{(A_1 \cup A_2) - (A_1 \cap A_2)}{(A_1 \cup A_2)}, 0 \leq E \leq 1 \qquad (2.2)$$

where A_1 and A_2 are the total landslide area in the first (A_1) and second (A_2) inventory (both at different scales); $\cup$ and $\cap$ are respectively the geographical union and intersection of the two inventories (Galli et al., 2008). Using GIS, a pair-wise geographical union and intersection of all three inventories was performed. This was accomplished by developing a contingency table which identified disagreement between stable and unstable slopes. The contingency table assessed the disagreement between landslide densities by plotting each of the three maps' stable and unstable map units against each other, i.e. Map A to Map B, Map A to Map C, Map C to Map B. From Equation 2.2, the degree of matching, *M*, between the inventory maps was measured using Equation 2.3. The products of this equation were used to form the contingency tables for disagreement analysis (2008).

$$M = 1 - E, 0 \leq M \leq 1 \tag{2.3}$$

Galli and fellow authors conclude that the multi-temporal map at 1:10,000 scale was far superior to the geomorphological map (also at 1:10,000 scale) or the reconnaissance map at 1:100,000 scale (Galli et al., 2008). Overall mapping error is smallest (0.66) when the multi temporal map is compared to the second most accurate map, the geomorphological map. The degree of matching ranged from 0.34 and 0.19. Yet, it is very costly and time consuming to create a multi-temporal map at fine scales. Much of the variability between the maps studied by Galli et al. (2008) was identified in the process of building the maps themselves. Up-scaling factors and human error were the main contributors to this variation (Galli et al., 2008).

It is important to note that Galli and fellow authors additionally attempted to separate drafting and digitisation errors of building landslide maps by drawing buffers of increasing sizes around the mapped landslides using a raster model (2008). Raster modelling is explained in the following section. Galli et al. (2008) believed this method identified the inaccuracy in transferring landslide information from aerial photographs to the base map, including digitisation errors, which accounted for a buffer of approximately 10 m for the 1:10,000 scale maps (both the geomorphological and multi temporal maps) and 50m for the 1:25,000 scale map (reconnaissance map).

Galli et al. (2008) further analysed the three maps using specialised software. The software derived drainage and divide lines using a 10 m × 10 m Digital Terrain Model (DTM) to identifying slope units, which are the terrain units of reference in this study. Then using a GIS, the landslide density —or landslide area— of the three inventories was compared. A scatter plot of the landslide density of one map was plotted against the density of a second to illustrate conformity when a higher density of clusters is seen. The two fine scale maps compared well against each other, showing the highest conformity.

Lin et al. (2005) investigated the variability of soil map units and soil properties at multiple scales through two case studies. The first study looked at the variability of soil components within a map unit, which was identified as "map unit purity or P_m," at map scales of 1:7,920, 1:24,000, and 1:250,000 in the Backswamp Watershed, South Carolina. They calculated the P_m, which is the area-weighted mean purity percent using the following equation:

$$P_m = \frac{1}{100} \int_{i=1}^{n} (P_i A_i) \tag{2.4}$$

where P_i (%) is the purity of unit i on a thematic map of a coarser scale, e.g. 1:250,000, as compared to a finer scale, e.g. 1:7,920 scale. A_i (%) is the percent area of unit i on a map and n is the total number of map units (excluding water bodies). The outcomes of the Backswamp Watershed study show $P_m =$ 65-85% for soil properties for the 1:7,920 scaled map (Lin et al., 2005). The P_m calculated for 1:250,000 and the 1:24,000 scale map were $P_m =$ 24-81% and 60-90% respectively (Lin et al., 2005). Therefore, according to this study the finer scale maps had the best map unit purity.

The second case study that Lin et al. (2005) investigated, involved 324 soil samples collected across the Minnesota River Basin. A nested hierarchical sampling design was used, which allowed for the analysis of variance of soil variability at multiple scales. Soil regions, hill slope positions, clusters, and point scales were the selected levels in the hierarchical design. Lin et al. (2005) cite Edmonds et al. (1985) in estimating the variance at each level of sampling design using the following expressions:

1. The variance (σ) of the location level with a given region: $\sigma_L^2 = \frac{MS_L - MS_C}{rpc}$

2. The variance of the cluster level within a given location: $\sigma_C^2 = \frac{MS_C - MS_P}{rp}$

3. The variance of the point level at a given cluster : $\sigma_P^2 = \frac{MS_P - MS_\varepsilon}{r}$

4. The total variance: $\sigma_T^2 = \sigma_L^2 + \sigma_C^2 + \sigma_P^2 + \sigma_\varepsilon^2$

where the number of points per cluster is r, p is the number of clusters per location, c is the number of locations per region, and ε is the residual or unexplained variance. MS stands for the mean square of a variable. Lin and fellow authors (2005) concluded that 50% of the spatial variability was seen at the local point scale. The hierarchical scale sampling method is recommended to determine at what scale variability will most likely occur for any given variable (Lin et al., 2005).

2.7.4 Raster Modelled Map Comparison Analyses

The use of raster based map comparison methods has increased as GIS software and hardware computational power has improved exponentially and new digital imagery technology, specifically in remote sensing, has exploded in the last few decades (Eldrandaly, 2007; Frank, Egenhofer, & Kuhn, 1991; Lurie & Irvin, 2002). Digital imagery is a raster format, as a pixel is synonymous with a raster cell. Spearheading this progress was the launching of commercially owned high-resolution satellites and the use of improved high resolution aerial imagery from commercial airplanes, which can provide better than 1 m ground resolution (Lurie & Irvin Jr, 2002). The availability of government-operated and owned remote sensing equipment, as well as the data derived from the equipment, such as the United States of America’s (US) Landsat satellite, has spurred innovation in imagery analysis used in studies around the world (e.g., Huang, Wang, & Zhang, 2012; Kaufmann & Seto, 2001; Nagar & Rawat, 1989).

It is possible to analyse the current vector modelled national LUC polygons and the two detailed LUC survey datasets outlined in Chapters 3 and 4 in raster format. This can be done by rasterising the datasets using GIS software. Rasterising the LUC datasets will generate a raster matrix with each raster cell containing a value (e.g., erosion severity, with values ranging from 0 to5), which can be analysed in an accuracy assessment. Congalton and Green (1999, pp. 8-10) explain the current theory of digital accuracy assessments using error matrices. An error matrix, also referred to as a confusion matrix, compares one set of data to another by generating a square array of columns and rows (Congalton & Green, 1999, p. 9). An example of an error matrix is seen in Figure 2.7. The columns of an error matrix represent a class (identified by an alphabetical label in Figure 2.7 and its associated agreement with the same class i.e., the number value) from a second data source, which is usually referenced data (Congalton & Green, 1999, p. 9). Agreement is measured by identifying the number of raster cells that show an error of inclusion (commission error) or an error of exclusion (omission error) of a particular class within a raster cell array. This method is similar to Galli et al. (2008) union and intersection based comparison methods of vector based data analyses previously mentioned. According to Congalton and Green (1999, p. 4), all accuracy assessments have four steps: designing the sample, collecting data for each sample, building and testing the error matrix, and analysing the results.

Reference Data

Classified Data		D	C	AG	SB	Row Total
	D	65	4	22	24	115
	C	6	81	5	8	100
	AG	0	11	85	19	115
	SB	4	7	3	90	104
	Colum Total	75	103	115	141	434

Figure 2.7: Example of an accuracy assessment.

Where land cover categories are as follows: D = deciduous, C = Conifer, AG = agriculture, and SB = shrub. The Producers Accuracy would then be D (65/75 * 100) = 87%, C (81/103 * 100) = 79%, AG (85/115 * 100) = 74%, and SB (90/141 * 100) = 64%.

(Reproduced from Congalton & Green, 1999, p. 9)

Maingi et al. (2002) perform an one-to-one or hard classification accuracy assessment on a 1992 land cover map of the Upper San Pedro Watershed, US/Mexico. The US Environmental Protection Agency (EPA) supplied the Arizona Remote Sensing Center with 60 digital orthophoto quads (DOQs) to use as reference datasets for land cover derived from the Landsat Multispectral Scanner System (MSS) (Maingi et al., 2002). Maingi et al. (2002) sampled 457 points for land cover class by using a stratified (by land cover class area) random sampling design. A minimum of 20 samples for the smallest class was also used. Classification accuracy for this study was found to be roughly 75% using error matrix methodology.

Latifovic and Olthof (2004) analysed coarse spatial resolution data using sub-fractional error methodology. Silván-Cárdenas & Wang (2008) define this as a soft classification procedure, which involves the classification of a single pixel when multiple classes are present, by its proportions of different classes as compared to the standard hard comparison classification (Latifovic & Olthof, 2004). The authors were interested in the homogeneity of a coarse landscape remotely sensed imagery classification, which is defined as the fraction of dominant land cover in an area (Latifovic & Olthof, 2004). The software *Accuracy Assessment Analysis (A^3)* was used to perform an accuracy assessment under multiple scenarios to quantify the influence of spatial and thematic resolution on raster-derived land cover data. Latifovic and Olthof looked at four 1 km resolution global land cover datasets of the Canadian boreal forest. All maps were reclassified to have a common legend. This action can cause reduction in accuracy due to limited transferability between maps (Latifovic & Olthof, 2004). A series of areally-derived 30 m resolution Landsat reference datasets and the four course resolution global land coverages were used to create a sub-fractional error matrix. The overall accuracy in this study when separating forest vs. non-forest area was 91%. 80% accuracy was seen when separating the classes into six elementary land cover types (Latifovic & Olthof, 2004).

Fuzzy logic, a form of soft classification, is a possible avenue when comparing thematic maps and imagery. Congalton and Green (1999, pp. 77-79) explain, "Fuzzy logic recognises that, on the margins of classes that divide a continuum, an item may belong to both classes". A situation when this theory could be used is seen when the national standard LUC map has a map unit classified as 100% 7e11 and the detailed LUC map has the same spatial area divided into 10% 6e21, 20% 6e8, and 70% 7e11. In this case, it is acceptable to say the true class of this LUC map unit is 7e11. Thus, a set of rules must be designed to allow for a degree of acceptability (see Congalton & Green, 1999, p. 77 for a further understainding of Fuzzy logic theory).

Table 2.5 summarises the previous cited vector and raster map comparison models. The table also provides an example of how each model can be used to investigate the thesis research questions.

Table 2.5: List of Cited Map Comparison Methodologies, Their Applications, and Prospective Use In This Study.

Reference	*Method/Technique*	*In what situation is this method applied*	*How the method could be applied in this study*
Basayigit & Senol, 2008	% Area Conformity & Descriptive statistics using arithmetic mean (ANOVA)	This methodology was used to compare vector data, i.e. tabular characteristics and attributes, to identify the variance between attributes.	This method could be used to identify the variance in area conformity between the national standard and fine resolution LUC map units.
Galli et al., 2008	Pairwise comparison, Overall Error, and Degree of Match models, Buffer analysis, Multivariate Statistics using Degree Matching (Scatter plot)	This methodology was used to compare vector data. This methodology uses contingency tables to compare disagreements of attributes mapped. Buffers were used to identify map production error. Multivariate statistics can also help to show variance between attributes.	This method could be used to show the level of conformity between map units of the national standard LUC map and the detailed LUC maps. Buffers can be used to identify levels of map production error. Multivariate Statistics can be used to identify LUC class over/under estimation.
Lin et al., 2005	Unit Purity model, Nested Hierarchical Sampling design	This model was used to compare vector map units between multiple maps by measuring purity rather than mean values of attributes. The nested hierarchical sampling design will reduce statistical error of point data.	This method could be used to show the level of conformity between map units of the national standard LUC map and the detailed LUC maps. The sampling design could be used for selecting field survey sample locations and/or used for modelling variance of vector data attributes.
Congalton & Green, 1999	Accuracy Assessment	This method was used to compare raster map units using an error matrix to identify commission and omission error in both producer and user accuracy.	After rasterising vector data obtained for this proposed study, an error matrix can be performed to identify the level of conformity between the national standard and detailed LUC maps.
Maingi et al., 2002	Hard Accuracy Assessment, Stratified random sampling design	This method was used for a one-to-one comparison of pixels in a raster array. The sampling design was used to reduce statistical error.	One-to-one raster comparison can be used in this proposed study to identify conformity. Error matrices can be used to understand identified levels of conformity. Stratified random sampling design could be used to identify survey locations for LUC calibration and accuracy assessment.
Latifovic & Olthof, 2004	Soft Accuracy Assessment	Using sub-pixel fractional error matrices to quantitatively re-class pixels by their dominant class	This method could be used to identify levels of conformity between maps. This method could focus on the degree of difference between LUC classes 1-6 and 7-8.
Congalton & Green, 1999	Fuzzy Set Theory	Fuzzy Set Theory establishes rules to adjust accuracy of collected raster data.	Fuzzy Sets can be used by creating rules that can better identify LUC units from a raster array, e.g. establish a set of rules for labelling pixels based off of LUC classes 1-5, 6, and 7-8.

This chapter provided a background on soil erosion in NZ and reviewed NZ's LUC and proposed ESC systems, designed to help manage erosion. Chapter 2 also provided background on the MAUP and reviewed methods used to quantify the degree of spatial uncertainty between two maps using GIS.

Erosion is a natural process; however, it is often accelerated by anthropogenic means, most notably stemming from poor planning (Coker & Fahey, 1993). Quite often erosion can be mitigated by proper design and location of potentially erosion-predisposing engineering works such as roads and log landing platforms. As Marden (2012) and other studies have shown (e.g., Fahey, Marden, & Phillips, 2003; Phillips, Marden, & Basher, 2012), the continued use of plantation forestry for erosion mitigation is a possible option, which will benefit NZ as a whole, as the forestry industry is a leading contributor to the NZ economy.

Erosion management policy, which seeks to mitigate erosion through managing agricultural production and soil use, saw the development and usage of NZ's LUC system and the NZLRI as tools for erosion policy framework. These systems came about through many years of experience. It is important to be adaptable to changing technology (i.e., updating a system with finer spatial resolution and more accurate data) and to the fluidity of social objectives. It is equally important to update data as new and finer resolution data becomes technologically and economically feasible. The introduction of the GIS and the subsequent transfer of the LUC and NZLRI to a geospatial database was a step in this direction.

This chapter reviewed a subset of possible GIS methods, used to quantify spatial uncertainty. Basayigit and Senol (2008), Galli et al. (2008), and Lin et al. (2005) provided vector modelled methods, while Maingi et al. (2002), Latifovic and Olthof (2004), and provided examples of raster modelled GIS methods. A hard classification accuracy assessment, similar to Maingi et al. (2002), was chosen as an analysis method for this study and is described in more detail in the next chapter.

2.8 The Research Problem

A national erosion susceptibility classification (ESC) system has already been finalised as a tool for assessing if an entity conducting plantation forestry requires a notification or non-notification resource consent due to possible adverse erosion effects of the forestry activities. This thesis investigates the need for finer resolution of the underlying LUC data of the ESC, if it is to be used for local level planning. The literature in this chapter supports the need to understand the scale problem associated with the ESC system in the proposed NES for Plantation Forestry.

Chapter 4 will attempt to use the Melton ratio (derived from GIS analysis of NZ River Environment Classification (REC) order 1 polygons) as an independent erosion discriminating variable, which can be used in GIS modelling for erosion severity. Then an assessment of the uncertainty between erosion severity mapped in a LUC inventory at a spatial resolution of 1:10,000 (i.e., Burton, 2010; Todd et al., 2012), against the current national LUC inventory (i.e., Landcare Research, 2002a; Landcare Research, 2002b) mapped at a spatial resolution of 1:50,000 will be conducted. This will quantify the agreement between the 1:50,000 LUC survey used to derive the national ESC, versus a local LUC survey mapped at a fine resolution. Chapter 5 provides a second test of uncertainty, using the same methodology as Chapter 4, but covering 1:10,000 LUC inventory from a broader geographical area (Todd et al., 2012).

2.8.1 Research Questions

To accomplish the objectives outlined in Section 1.2.2, the following research questions will be investigated to quantify a measurement of uncertainty between the 1:50,000 LUC survey (used to derive the proposed ESC system), versus local LUC surveys mapped at 1:10,000 scale:

1. What is the level of agreement (association) between the Melton ratio of REC order one polygons and erosion severity measurements of LUC areal map units, generalised at spatial map scales of 1:50,000 or 1:10,000

2. What is the level of agreement between the erosion severity categories measured in the sampled 1:10,000 scale LUC survey, as compared to the same extent in the national 1:50,000 scale NZLRI LUC survey

Understanding the degree of agreement or uncertainty between the measurements of erosion severity and their areal map units may give decision makers the ability to more adequately judge the variability of erosion over a landscape.

Chapter 3 Materials and Methodology

3.1 Introduction

The first section of this chapter describes the location, historical and current land use, climate, geology, and soils of the two case studies assessed in this thesis. The first case study was located in the Sherry River Catchment in Tasman district, in the north of the South Island. The second case study was located in the Horizons Region, located in the south-west of the North Island

The second section of this chapter contains a data map, which provides the sources and data used in this thesis. This is followed by the overall design of the study and ends with the description of the analysis conducted to investigate the research questions.

3.2 Location: Sherry Catchment Case Study

The Sherry River catchment is located in the north of the South Island in NZ’s Tasman Region (Figure 3.1). The Sherry River catchment was the boundary and Region of Interest (ROI) for this case study. Matariki is the closest locality to the study area. The Sherry River is part of the Motueka River system and is a tributary of the Wangapeka River.

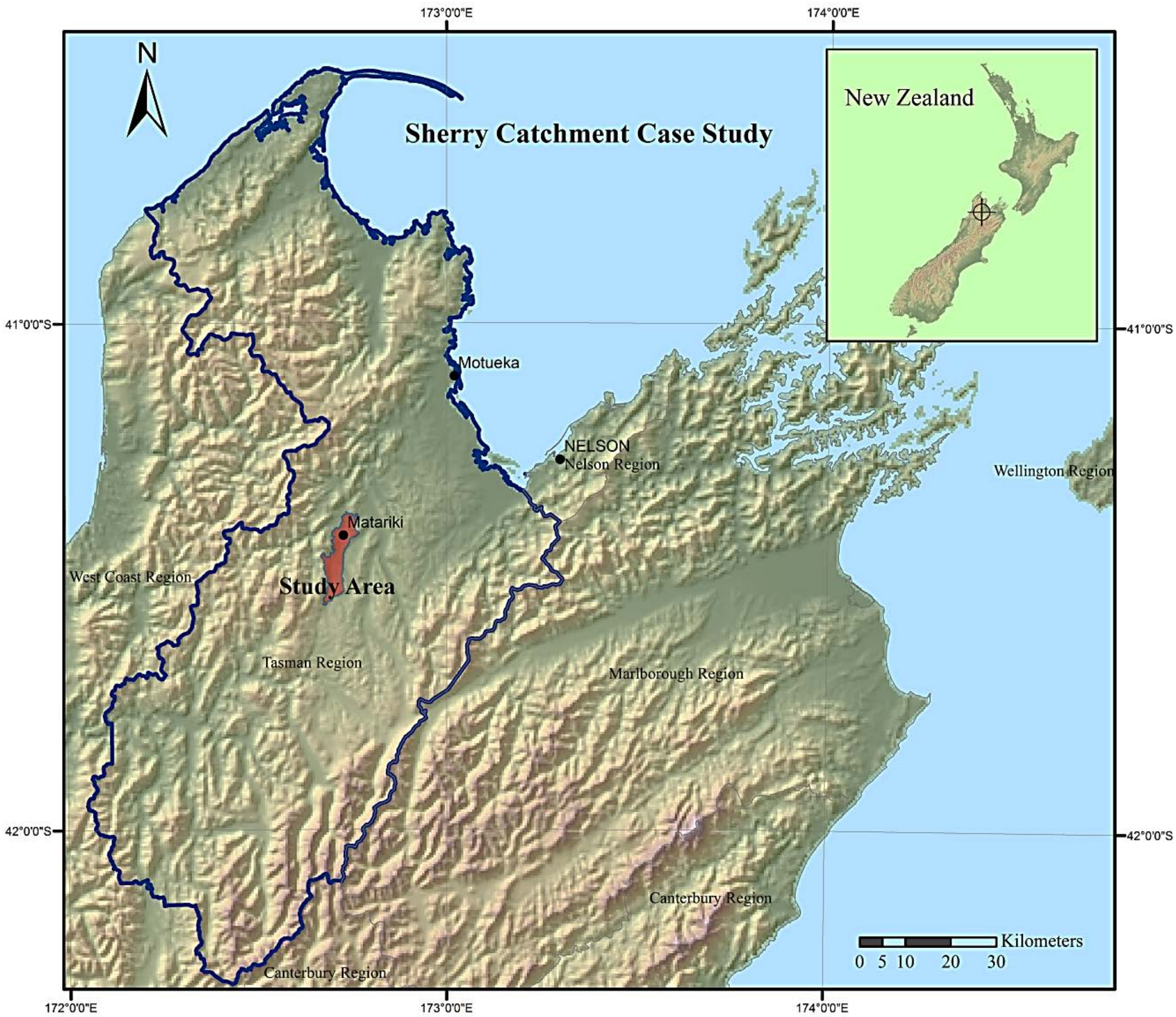

Figure 3.1: Location of the Sherry Catchment Case Study, Tasman District, SI New Zealand.

The case study area covers 6614 ha and was selected because of data availability and a recent LUC survey of the area. The areas of interest (AOIs) of the Sherry Catchment Case Study consist of 13 drainages, with a total area of 383 ha, all on the west side of the study area (Figure 3.3). How and why the AOIs were chosen is discussed in the design section of this chapter.

3.2.1 Land Use

The Sherry River catchment has been used by humans since the initial settlement of NZ's indigenous people. The area was used as a resting site for Maori seeking pounamu (greenstone) on the West Coast (NZ Landcare Trust, 2010, p. 8). The Sherry River catchment became densely settled by Europeans during the 1864 gold rush and has since experienced a succession of sawmilling, sheep farming, horticulture (hops and raspberries), forestry, and dairy farming activities (NZ Landcare Trust, 2010, p. 9). Currently, 35% of the upper Sherry River catchment is managed by P.F. Olsen and Co. for forestry production, and is owned by the Tasman District Council. Sheep farming and small herds of dairy cattle are still present in the Sherry River valley.

3.2.2 Climate

The mean elevation of the Sherry River catchment is 371 m, with a maximum of 760 m and a minimum of 180 m (LINZ, 2012). The mean annual temperature across 70 Land Environments of New Zealand (LENZ) order 1 mean annual temperature polygons (MFE, 2011b) within the extent of the Sherry River catchment was 9.9°C, with a maximum of 12°C and minimum of 7.5°C. The annual water deficit, sourced from LINZ order 1 mean annual water deficit polygons of the same extent was 49 mm, with a maximum of 134.65 mm and minimum of 0.94 mm.

3.2.3 Geology

Within the Sherry River Catchment, the dominant near-surface lithology is the Separation Point Granites, while the river basins are alluvium derived from sandstones, siltstone, and mudstone (NZ Landcare Trust, 2010, p. 6). Separation Point Granites are a petrographically distinct igneous belt, which are more susceptible to weathering than other granites in NZ (Gage, 1980, p. 140). These granites are lighter in colour than other granite formations in New Zealand, comprising of sodium-rich oligoclase, rather than potassium-rich orthoclase, and darker mineral hornblende, instead of biotite mica (Gage, 1980, p. 140).

Figure 3.2 provides a map of the parent rock material of the study area (i.e., the geological near-surface lithology of the Sherry River catchment).

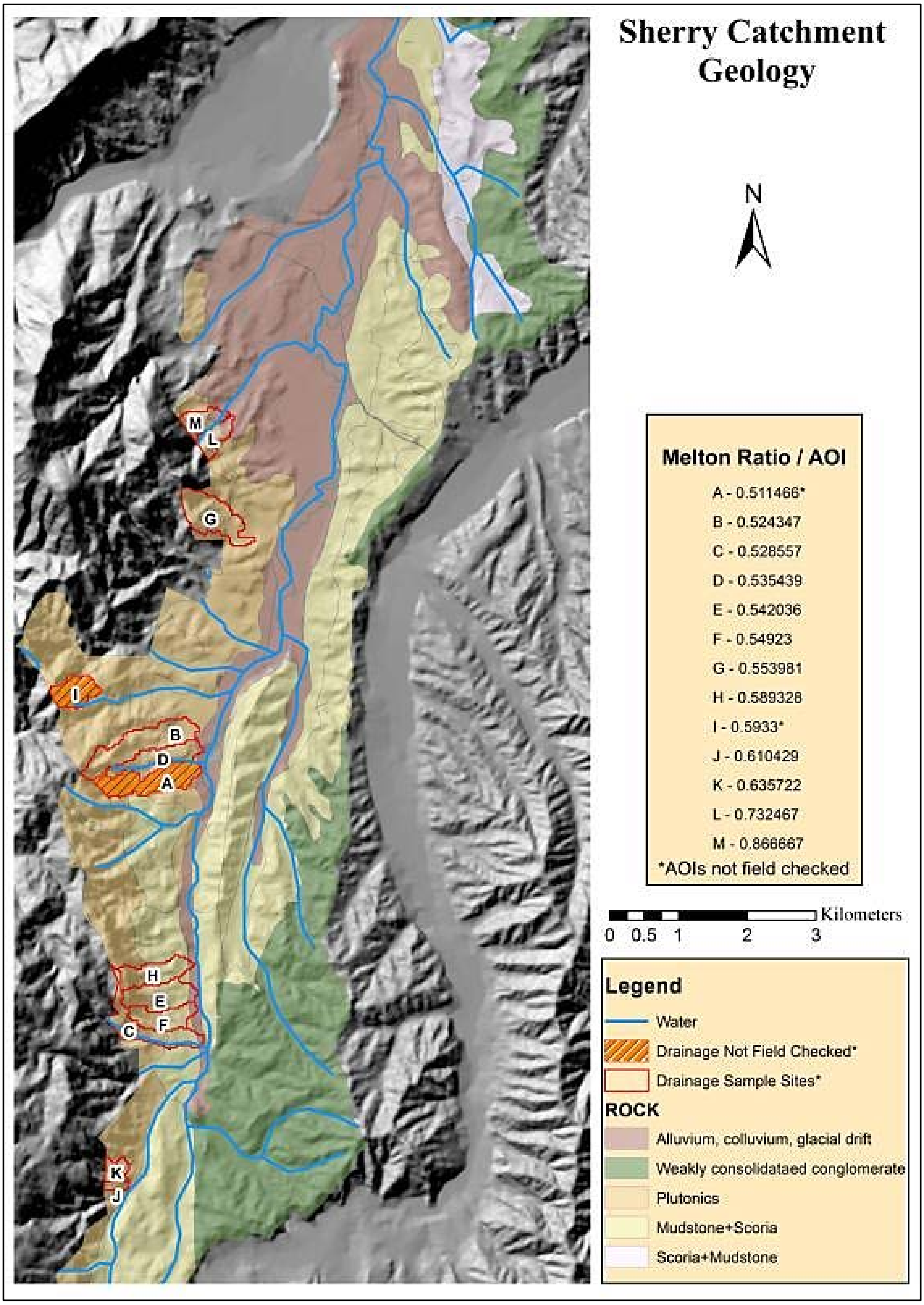

Figure 3.2: Geological map of the Sherry River catchment, which was produced from near surface lithology recorded in the NZLRI.

3.2.1 Soils

Figure 3.3 provides the series and type of soils within the Sherry River catchment, defined by the NZLRI and its underlying data sources (Landcare Research, 2011). The AOIs in this study comprised mostly Glenhope and Kaiteriteri soils, derived from weathered granite and granite colluvium.

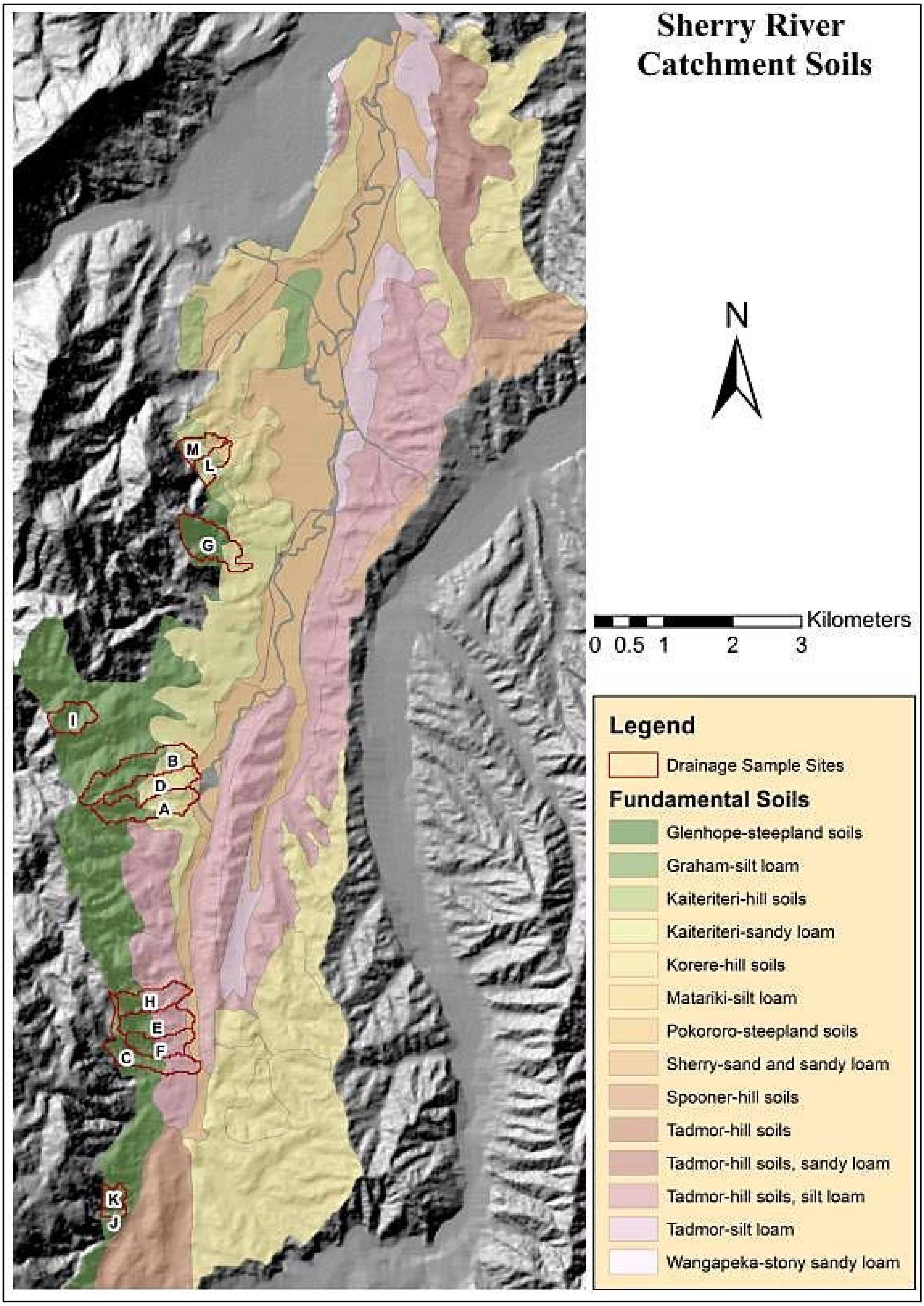

Figure 3.3: Soil map of the Sherry River catchment, which was produced from the fundamental soils layer recorded in the NZLRI.

3.2.2 Purpose of the Tasman LUC Survey

The LUC surveys used in the Sherry River Catchment Case Study were each published at a different scale. The national NZLRI LUC survey used in this thesis was published at a 1:50,000 map scale and can be downloaded from the LRIS Portal (Landcare Research, 2000b), while the Tasman LUC survey, which was published at a 1:10,000 map scale, was provided by Andrew Burton (2010) of the Tasman District Council. The purpose of the Tasman LUC survey was to assist in local and farm scale environmental planning of the Sherry River catchment in support of the Sustainable Farming Fund, facilitated by the Ministry of Agriculture and Forestry (Burton, 2009, p. 4). Thus, a difference in erosion severity measurements is expected between the two surveys because of 1) different spatial resolutions; 2) differences in the time of erosion severity assessment and 3) differences in the observers making the erosion severity assessment. Jones (1997, p. 14) explains that "the power of a GIS in the context of planning is dependent upon the ability to view information at different level of detail or generalisation to generate solutions to planning problems and to perform analyses of relative merits of alternative solutions." This study attempts to quantify the difference in LUC map units and their erosion severity measurements through a pair-wise analysis of the sample Tasman and reference NZLRI LUC surveys. The LUC map units and their corresponding erosion severity categories identified in the AOIs of this case study are listed in Appendix 1.

3.3 Location: Horizons Case Study

The Manawatu-Wanganui Region, managed by Horizons Regional Council, covers ten authorities and extends across ≈ 2.2 million ha of land (Figure 3.4). The region is located in the south-west of the North Island, NZ.

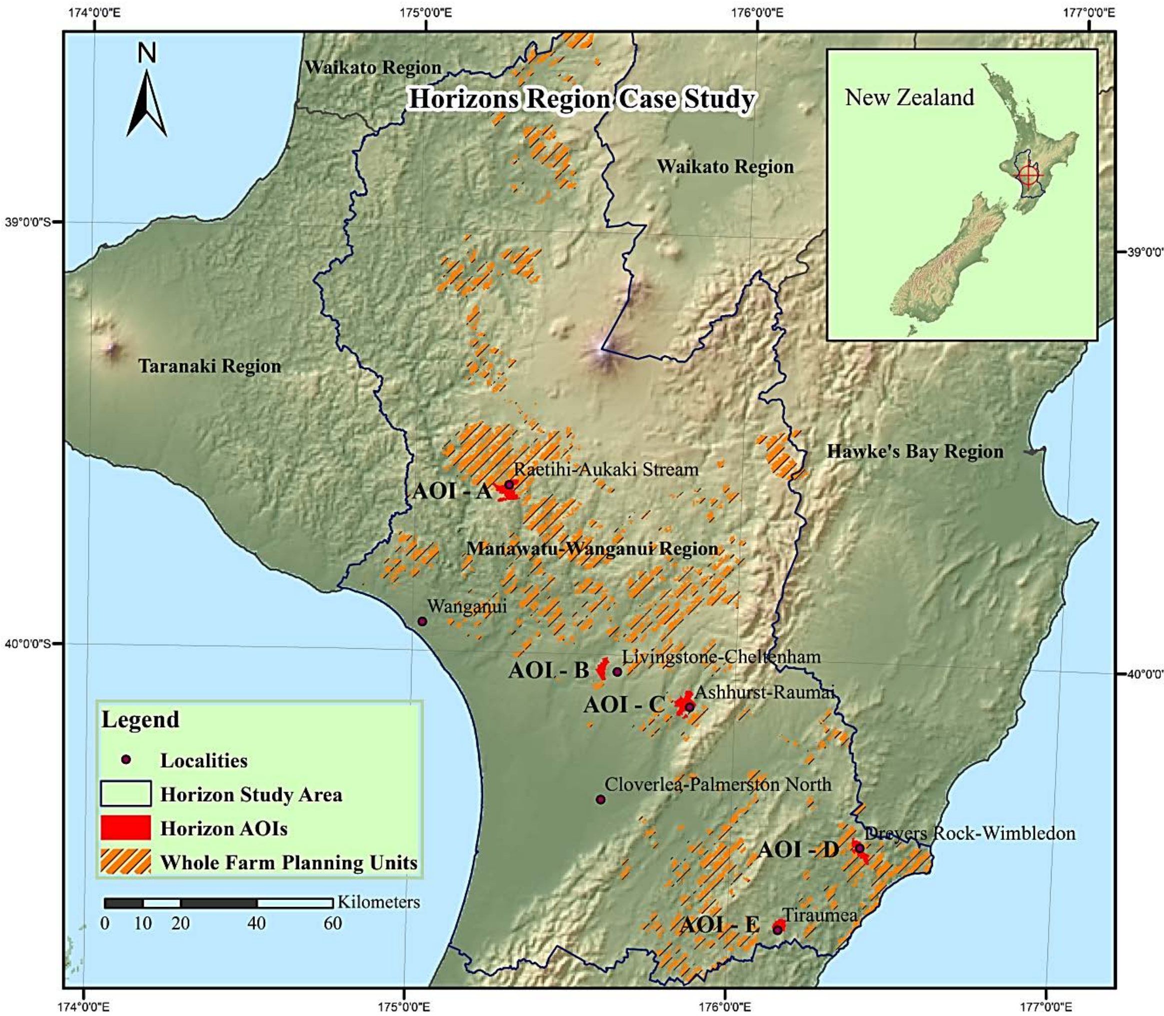

Figure 3.4: Location of Horizons Case Study, including the AOIs and extent of Whole Farm Planning in the Manawatu-Wanganui Region.

Around 286,000 ha of this land was surveyed for Whole Farm Planning in support of the Sustainable Land Use Initiative (SLUI). Further literature on SLUI can be found on Horizons Regional Council’s web page (see Horizons Regional Council, 2012b, 2012c). Five AOIs, ≈ 7,372 ha, were selected for this case study and were labelled AOI A-E in Figure 3.4. The AOIs were identified by one of the original surveyors, Malcolm Todd of the Horizons Regional Council, with the intent of providing a representative subset of locally LUC surveyed land, which covered a wide variety of terrain and erosion severity categories.

3.3.1 Land Use

The Manawatu-Wanganui Region, also known as the Horizons Region, was populated by Maori for some time from the earliest days of Polynesian settlement, with no less than seven iwi (largest social group of the Maori culture) inhabiting the Horizons Case Study area (as cited in Rusden, 1865). Organized European settlement began in 1841 with the establishment of New Plymouth and Wanganui, yet it was not until 1850 that farming started in the region (Fletcher, 1987, p. 11). Dairy was the primary farming type with wheat being grown in the dryer areas of the region (Fletcher, 1987, pp. 10-11). In 1880, the opening of a rail line between New Plymouth, Palmerston North, and Wellington allowed for further expansion of dairy farming in the region (Fletcher, 1987, p. 11).

The Manawatu-Wanganui Region is currently home to 220,089 people (Horizons Regional Council, 2012a). Present land uses in the Manawatu-Wanganui Region includes livestock, forestry, and horticultural activities. Livestock is the primary agricultural land use within the region (51%) (Horizons Regional Council et al., 2012). Approximately 7.6% of the Horizons area is exotic plantation forest (Horizons Regional Council et al., 2012) and 30.9% of the Horizons region is under native vegetation cover (Horizons Regional Council et al., 2012).

3.3.2 Climate and Topography

Most of the Manawatu-Wanganui Region suffers from pronounced soil moisture deficits during the summer and autumn months, due to strong winds and moderate annual rainfalls (800-1200 mm) (Molloy, 1998, p. 99). Temperatures vary widely throughout the region with altitude and distance from the coast.

Table 3.1 lists each AOI’s maximum, mean, and minimum values of elevation, mean annual temperature and annual water deficit for LENZ order 1 polygons, associated climate attributes annotated within the spatial extent of each AOI. The number of LENZ polygons was also provided. The elevations provided in the following table were assessed using LINZ 1:50,000 contour lines (LINZ, 2012). Climate information was sourced from the Land Environments of New Zealand (LENZ) classifications system, order 1 polygons (MFE, 2011b). See LINZ *Technical Guide* for an understanding of the development and assessment of LINZ environmental units (Leathwick et al., 2002).

Table 3.1: Climactic Data For The AOIs of The Horizons Case Study.

	Elevation (m)	Mean Annual Temperature (° C)	Annual Water Deficit (mm)
	AOI - A	*Number of Polygons =*	2
Maximum	660	11.8	133.3
Mean	479	11.7	76.6
Minimum	180	11.6	19.9
	AOI - B	*Number of Polygons =*	11
Maximum	400	12.4	134.7
Mean	298	12.0	99.3
Minimum	140	11.6	19.9
	AOI - C	*Number of Polygons =*	11
Maximum	420	12.4	134.7
Mean	325	11.9	67.4
Minimum	140	10.5	19.9
	AOI - D	*Number of Polygons =*	1
Maximum	360	11.6	19.9
Mean	207	11.6	19.9
Minimum	60	11.6	19.9
	AOI - E	*Number of Polygons =*	2
Maximum	460	12.4	67.4
Mean	318	12.0	43.6
Minimum	140	11.6	19.9

The mean annual temperatures are similar in all AOIs, while the maximum and minimum elevation variances are due to the changing landscape between each AOI.

3.3.3 Geology

The following geological information, which represents each AOI in the Horizons Case Study, was sourced from the NZLRI LUC survey *rock* attribute field (Landcare Research, 2000a). The data represents the near-surface lithology of each AOI's extent and was mapped in Figure 3.5. This map illustrates the substantial differences in geology between all AOI's. Geology is an important factor in determining erosion severity and was part of the decision making process in generalising LUC areal map units. Most of the near-surface lithology in the Manawatu-Wanganui Region is sedimentary rock; highly erodible sand and mudstones, generally younger in succession and representative of the late Cretaceous to early Pleistocene periods (Gage, 1980, p. 34). The Alpine, West Wairarapa, and Wellington faults run northeast along the mountain ranges of the East Manawatu-Wanganui Region (Gage, 1980, p. 286). The mountain ranges in the Horizons Case Study area include the Ruahine, Kaimanawa, and Kaweka ranges. In the northern area of the region, the Tongariro volcanic zone is present (Fletcher, 1987, p. 9).

The geology of AOI A was predominantly undifferentiated alluvial sediments (Figure 3.5). The principal rock type in AOI B was a stratigraphic succession of loess (surface rock) followed by fine sandstones. Other fine to coarse sandstones are present in AOI B with a combination of unconsolidated to moderately consolidated clays, silts, sands, tephra and breccias. AOI C also showed a presence of the same clays, silts, sands, tephra and breccias, along with coarse massive sandstone deposition and three gravel deposits. AOI D's near-surface lithology was mostly jointed fine siltstones with some banding. AOI E was mapped as mostly fine mudstone to banded sandstones with some coarse sandstone deposits.

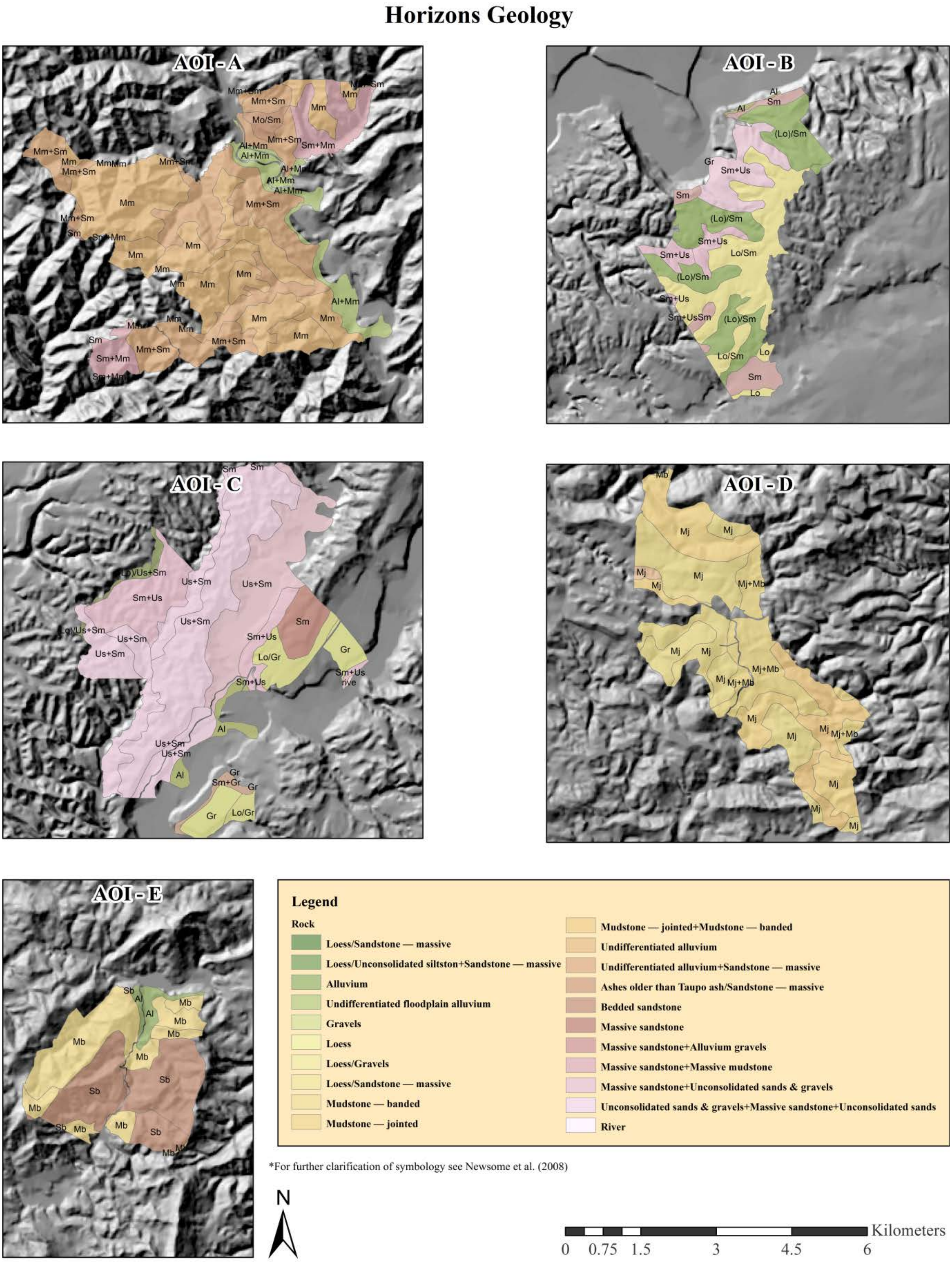

Figure 3.5: Geological map of all AOIs in the Horizons Region Case Study.

3.3.4 Soils

All soils mapped in Figure 3.6 and described below, were sourced from the Fundamental Soils Layer (FSL) (Landcare Research, 2011b). Soils were also used in the generalisation of LUC areal map units; thus, understanding the spatial extent and the pedology of the regolith is important and directly linked to the previously explained geology.

For further understanding of soil groupings in the FSL, see the *Data Dictionary* (Newsome et al., 2008), which can be downloaded from the Land Resource Information system (LRIS) Portal (see Landcare Research, 2011b).

The dominant soils and soil textures for each AOI in the Horizons Case Study (Figure 3.6) were as follows: AOI A is primarily Pahiatua silt loam with some Mangatea clay loam soil units; AOI B is mainly Halcombe silt loam soils with Whangaehu loam in the flats; most of AOI C was mapped as Pohangina sandy loam and Opawe sandy loam soils; AOI D was surveyed primarily as Mangatea clay loam and slit loam soils; and the dominant soils in AOI E were Mokau loam and Mahoenui silt loam.

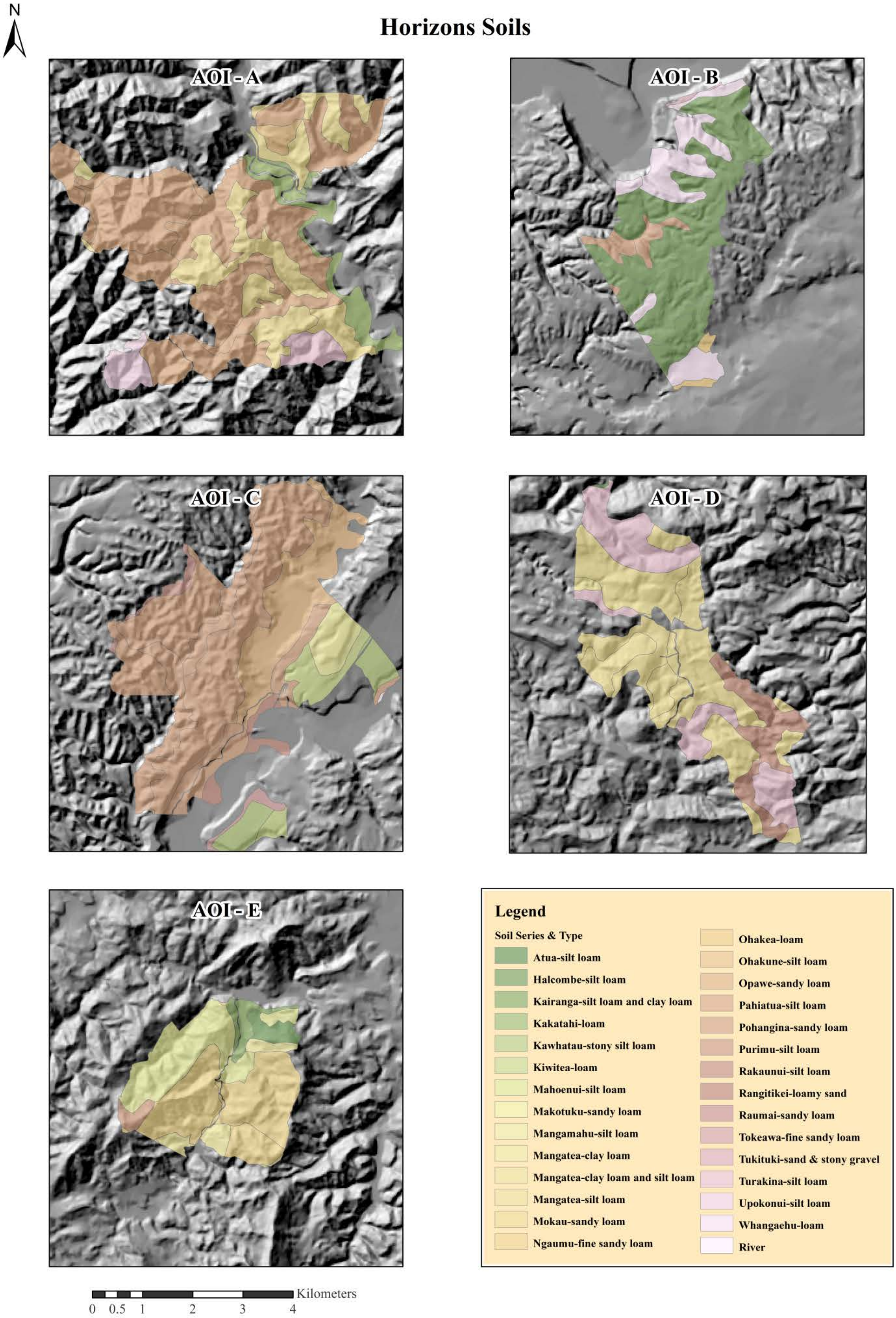

Figure 3.6: Soil map of each AOI in the Horizons Region Case Study.

3.3.5 Purpose of the Horizons LUC Survey

The Horizons Case Study compared the erosion severity measured in two LUC surveys, each measured at a different map scales. The sample Horizons LUC (Todd et al., 2012), was provided by Malcolm Todd of the Horizons Regional Council and was mapped at, 1:10,000 map scale. The purpose of the Horizons LUC survey was to assist in Whole Farm Planning (further explained in Horizons Regional Council, 2012c) for the Horizons Regional Council's Sustainable Land Use Initiative (further explained in Horizons Regional Council, 2012b). The Horizons LUC survey was measured in accordance with the current and preceding *LUC Handbooks* (Lynn et al., 2009; NZ MWD & SCRCC, 1971). The measurement of interest in the Horizons Case Study was the erosion severity class, with each LUC map unit having an empirically-estimated value. The erosion severity classes associated with LUC map units and recorded in the Horizons LUC survey are equivalent to the erosion severity classes of the NZLRI LUC survey.

3.4 Data

The following section provides a data map which outlines the sources and data used to produce the maps, realise the sampling dataset for statistical analysis, and conduct GIS analyses within this thesis. This will be followed by a brief outline of the main data used in both case studies, which include erosion severity and the ESC system.

Table 3.2: Data Map Outlining the Use and Sources of the Data Used Within This Study.

Data	*Source*	*Use*
ESC system	MFE (2011a)	Research variables and mapping
Horizons LUC Survey	Todd et al. (2012)	Research variables and mapping
Horizons Whole Farm Planning Units	Todd et al. (2012)	Location data and mapping
LENZ order 1 polygons	MFE (2011b)	Location data
NZ Addresses	Koordinates.com (2012)	Location data and mapping
NZ DEM 500 metre	University of Canterbury (2012)	Location data
NZ DEM North Island 25 metre	Landcare Research (2002b)	Research variables and mapping
NZ DEM South Island 25 metre	Landcare Research (2002b)	Research variables and mapping
NZ Fundamental Soils Layer	Landcare Research (2011a)	Location data
NZ Regions	Koordinates.com (2012)	Research variables and mapping
NZ Rivers and Streams	Koordinates.com (2012)	Research variables and mapping
NZLRI LUC Survey	Landcare Research (2010)	Research variables and mapping
REC order 1 polygons	NIWA Research Ltd. (2009)	Research variables and mapping
Tasman LUC Survey	Burton (2010)	Research variables and mapping

3.4.1 Erosion Severity

Present and potential erosion have been identified as significant land management concerns in NZ (Lynn et al., 2009, p. 22). Amongst other reasons, the NZLRI classification system (Eyles, 1985) was developed to describe erosion so that land managers could make the appropriate decisions based on present erosion (current erosion severity) and the probability of future erosion (potential erosion severity). The NZLRI classification system uses erosion form and processes to define erosion types (Lynn et al., 2009, p. 22), previously discussed in Section 2.3. As mentioned, Table 2.1 provided a list of all erosion types identified in the NZLRI classification system. Erosion severity is ranked from 0-5 and is based on empirical judgment and areal extent. For example, Table 3.3 outlines the erosion severity criteria for debris-flow erosion. Further information on how erosion severity is measured can be found in the *LUC Hand Book* (Lynn et al., 2009, pp. 22-44). Erosion severity values for the NZLRI reference datasets were parsed form the ESC dataset as explained in Section 2.3.2.

Table 3.3: New Zealand Erosion Severity Classification.

Symbol	*Severity*	*Debris-Flow (% Area)*
0	Negligible	< 0.5
1	Slight	0.5 - 2
2	Moderate	2 - 5
3	Severe	5 - 10
4	Very Severe	10 - 20
5	Extreme	> 20

(From Lynn et al., 2009, pp. 24-25)

3.5 Design

3.5.1 Investigating Research Question 1: The Association of the Melton Ratio and LUC Survey

The Sherry Catchment Case Study investigated the premise that erosion severities derived from either the NZLRI or Tasman LUC survey, each surveyed at different map scales, correlate to the Melton ratio derived from GIS analysis of REC order one polygons in the same spatial area. It was expected that there were significant differences between the NZLRI and Tasman LUC surveys due to spatial resolution of the areal units used in both surveys; that is, map units at a finer resolution are more precise than at a coarser resolution due to the ability of the surveyor to more accurately measure and depict ground characteristics and processes at fine resolutions.

If a positive monotonic association is present, that is, if erosion severity increases (values 0-5) then the Melton ratio (values 0-1) will also increase correspondingly. As a result, the Melton ratio could then be used as an independent indicator of erosion severity. The correlation of these variables could then be tested against LUC surveys of different spatial resolution, testing for spatial sensitivity in LUC areal map units and erosion severity measurements.

Realisation of the Sample and Reference Dataset

To ensure equal spatial population areas of measurements between the sample LUC survey (local LUC at 1:10,000 scale) and the reference survey (NZLRI at 1:50,000 scale), the following procedures were followed using ArcGIS 10 Desktop (ESRI, 2011).

<u>Data cleaning</u>

This involved using a Visual Basic (VB) string command line to remove spaces from the LUC map unit attribute field and change any other data that needed to be cleaned. Nomenclature between the two LUC surveys must be identical for pair-wise spatial analysis.

The reference AOIs required the attachment of the ESC erosion severity measurements. A new field was created in each LUC survey's attribute table and labelled "MaxSev". The maximum polygon erosion severity (file name: PolyMaxSev) field of the ESC layer was then joined to both the sample and reference LUC surveys attribute table, by their "LUC" field. The ESC layer was provided by the MFE (2012a) and developed by Bloomberg, et al. (2011).

The erosion severity measurements of the sample AOIs are values measured by the assessors at a finer spatial resolution.

<u>Render spatially comparable AOI geographic extents</u>

After the raw data was cleaned and maximum erosion severity values were joined to each LUC survey, the reference dataset (NZLRI LUC survey) was clipped using the *Clip Analysis* tool from the *ArcToolbox* by the sample datasets (Tasman LUC survey and the Horizons LUC survey); the intent being, to render spatially comparable AOI geographic extents. To gain an exact spatial extent with no slivering, *Clip Analysis* was completed again, this time clipping the sample dataset by the reference dataset. This process rendered the same AOI feature from the sample dataset as compared to the reference dataset.

A systematic sampling method was conducted in this study, measuring erosion severity at two spatial resolutions and the Melton ratio. The GIS platform ArcGIS 10 (ESRI, 2011) was used to develop a systematic sampling methodology, which covered the extent of the sample and reference datasets at 10 m intervals for pair-wise analysis. This was accomplished by rasterising the vector sample and reference AOIs, using the *Feature to Raster* tool in the *Arc Toolbox* by the erosion severity category and Melton ratio attribute fields. The raster matrix was then converted into a point feature using the *Raster to Point* tool. Then the two point features, that is, the sample and reference datasets, were intersected using the *Intersect* tool. This operation provided a combined point dataset, where each point represents a sampled or referenced erosion severity measurement or the sampled Melton Ratio. This feature was then saved as a database file, which was imported into the statistical package R (R Core Team, 2012) for statistical analysis. Further description and GIS models of the realisation of each case study's dataset, will be provided in the subsequent results chapters.

GIS Flow Model and Calculation of the Melton ratio (R)

The REC debris-flow model outlined by Irvine (2011) was the GIS model used to calculate the Melton ratio, the first variable of interest in this case study. First order REC polygons (drainages) (NIWA Research Ltd., 2009) were used in this case study to reduce scaling effects and are further explained in the next paragraph. Irvine (2011) compared the REC debris-flow model to other GIS models of NZ, that is, those of Watts and Cox (2010) and Welsh and Davies (2011) as previously illustrated in Table 2.2, concluding that their Melton ratios were not significantly different. Due to minimal differences in Melton ratio calculations between models and data availability, the REC debris-flow model was chosen in this case study. All drainages with $R \geq 0.5$ were identified as having the Melton ratio most likely to identify debris-flow and therefore were selected as the AOIs for the case study. This threshold was chosen based on the work of Welsh and Davies (2011) and Irvine (2011). Welsh and Davies (2011) successfully used GIS debris-flow modelling and field investigation in the catchments of Coromandel and Kaimai Ranges of the North Island and meta-data from the South Island to predict debris-flow occurrence in areas with a wide variety of lithology, climate, and vegetation.

The REC order one polygons were downloaded from koordinates.com. It is important to note that the REC layers are generalised, interpolated data, and there are often spatial differences between the position of the REC layer and the actual passage of the water drainages. This could be due to the resolution of the underlying data, age, and other factors of the legacy data used to derive the REC layers. Figure 3.7 illustrates the numerical system of REC order catchments and can be further clarified by downloading the user guide and metadata with the REC polygons from koordinates.com. Irvine (2011) also used a Digital Elevation Model (DEM) to compute the maximum and minimum elevations required for the Melton ratio. The DEM used in the Sherry River Catchment Case Study covered the South Island and was downloaded from the Landcare Research Inventory System (LRIS) Portal (Landcare Research, 2002b). The DEM was produced using the following Land Information New Zealand (LINZ) 1:50,000 scale Topographic data layers: 20m contours, spot heights, lake shorelines, and coastline. A 25 m resolution raster was produced, which has 90% of the vertical data to within ± 5 m of their true elevation (Landcare Research, 2002b). Using the steps outlined by Irvine (2011) for calculating the Melton ratio of a catchment, a new shapefile was produced using the GIS platform, ArcGIS 10 (ESRI, 2011) for spatial analysis.

REC Polygon Order System:

First order polygons equal headwater streams. When two tributaries of the same order meet, the next section will have an increased order polygon. When two tributaries meet and one has a higher order than the other, the next section is labelled by the highest ordered section.

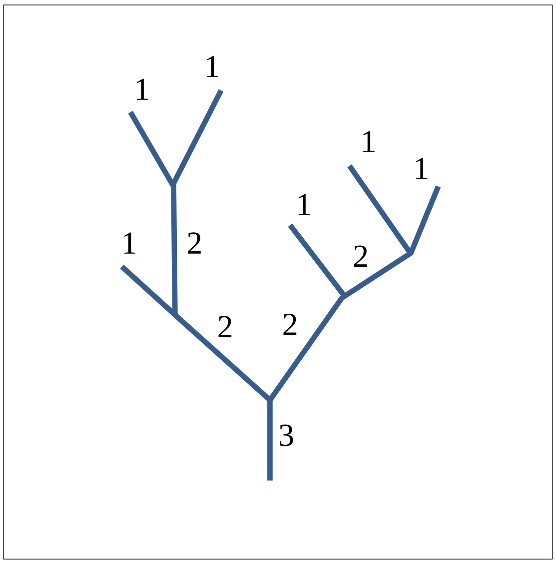

Figure 3.7: The REC stream order system, which uses a numerical position index of a tributary or section of a river within a drainage network.

(Reproduced from NIWA Research Ltd., 2009)

Debris-flow Field Assessment

A field investigation was conducted to calibrate the REC debris-flow model to the Sherry River catchment. Appendix 2 provides the field checklist used in the Sherry Catchment Case Study for identifying debris-flow (Kurtz, 2012). Two of the thirteen drainages were not visually inspected due to access limitations and were annotated in Figure 3.2. Only five drainages showed evidence of debris-flow (Kurtz, 2012). However, this could partly be due to fluvial erosional erasing surface evidence of debris-flow deposition.

3.5.2 Investigating Research Question 2: Spatial Thematic Accuracy

In the previously mentioned pair-wise comparisons, spatial agreement, a quantifiable measure of spatial uncertainty, was identified by performing an accuracy assessment and multivariate statistical modelling. A hard classification accuracy assessment, explained in Section 2.7.3, was chosen to quantify spatial and thematic agreement for the following reasons:

1. Temporal aspects
    a. Time needed to learn new software

   b. Time for developing an adequate model

2. Peer reviewed literature on the topic is readily available
3. The analysis provides a thematic estimation as well as a spatial measurements
4. With the addition of Kappa Correlation Coefficient (see Section 3.6.2) the hard classification provides a good geographical statistical inference
5. Costs (e.g., purchasing of new computer programs or usage rights for online applications)

Developing an Accuracy Assessment

Using the same sample and reference vector ROIs previously realised, each case study now has two shapefiles for pair-wise comparison, a sample AOI feature and a reference AOI feature. Using ArcGIS 10 both vector datasets were rasterised using the same methods previously explained, by erosion severity. Both the sample and reference raster matrices were combined using the *Combine* tool from the *ArcToolbox*. The *Table Select* tool was used to export the new combined erosion severity dataset, with a .dbf file extension, into Excel (Microsoft, 2010b). The Excel table lists all possible combinations of classifications between the reference map and the sample map, including the total cell count per classification respective to each survey. The database platform Microsoft Access (Microsoft, 2010a) was then used to perform a cross-tabulation query, forming the columns and rows of the error matrix. The matrix was calculated from the average count of the values registered in the cross-tabulation query. The cross-tabulation values are based on the number of common classified cells of a given category from the reference map, represented in the columns of the matrix, to that of the sample map, represented in the rows. The accuracy assessment conducted in this study will be further explained in the next section.

3.6 Analysis

This section will provide an understanding of how the thesis research questions were investigated. The first question looked for a correlation between the erosion severity variable, and the spatially weighted response variable, the Melton ratio. Sprent and Smeeton (2007, p. 283) define correlation as the "... measure of the strength of association or dependence between two variables." Because erosion severity is measured on the ordinal scale, Spearman's rank correlation coefficient was used as a measure of correlation. The statistical platform R (R Core Team, 2012) was used for statistical modelling in this case study and the statistical significance level was set at $\alpha = 0.05$. However, due to the presence of spatial autocorrelation, the resulting p-values are likely to be underestimated (i.e. reporting higher significance that is really the case). As mentioned earlier, autocorrelation simply means that neighbouring areas are more alike than further away areas. However, the statistical tests herein are still effective due to the amount of detail known about variables of interest and environmental interactions. The first research question examined only the Sherry River Catchment Case Study and its results will be reported in the following chapter.

This section will also provide the description of the analysis for the second research question of this study, which tested the measure of agreement between the reference dataset of the 1:50,000 scale NZLRI LUC survey, to the two sample 1:10,000 map scale datasets, the Tasman and Horizons LUC surveys. The LUC areal map units and their erosion severity categories were the identified units of interest within each dataset. Both variables (LUC map units and erosion severity values) were ranked and ordinal in nature. A Spearman's Ranked Correlation Coefficient was calculated to test the association of erosion severity measurement between the reference and sampled LUC surveys. The statistical significance level for these models was also set at $\alpha = 0.05$. This test identified the correlation and thus consistency of surveyor judgment between the referenced and sampled LUC surveys identify in this thesis. To test the measure of agreement of the erosion severity attribute between the referenced and sampled LUC surveys, an accuracy assessment was performed. An overall accuracy of ≥ 85% was set to identify a significant agreement (Congalton, 2008b, p. 56). A Kappa statistic was then calculated to gain insight into the goodness-of-fit between erosion severity values measured at two different scales (Sample 1:10,000 and Reference 1:50,000).

3.6.1 Testing Research Question 1:

What is the level of agreement (association) between the Melton ratio of REC order one polygons and erosion severity measurements of LUC areal map units, generalised at spatial map scales of 1:50,000 or 1:10,000

Contingency Table

Contingency tables were produced to assess the joint distributions of perceived erosion severities for both reference and sample LUC surveys for designated AOIs. For each AOI, a spatially weighted Melton ratio was calculated (Eq. 2.1). The contingency table in this study also shows the percent area per erosion severity category of each LUC survey.

Spearman's Ranked Correlation Coefficient

The Spearman's ranked correlation coefficient (Spearman, 2010) or Spearman's rho (ρ, Equation 3.1), was used to evaluate for the units of interest in both surveys.

$$\rho = 1 - \frac{6\sum D^2}{N(N^2-1)} \tag{3.1}$$

where D = the difference between the ranks of corresponding values X and Y and N = the number of pairs of values. A rho of 1 corresponds to a perfect positive monotonic relationship and -1 identifies a perfect negative relationship, while a rho of 0 equals no relationship at all

(Sprent & Smeeton, 2007, p. 287). The Spearman's ρ is the Pearson coefficient, but ranks replace the continuous data (Sprent & Smeeton, 2007, pp. 286-287). The Spearman's ρ is appropriate for testing for trends or when testing for equivalence between ranks, or orderings assigned by two evaluators (Sprent & Smeeton, 2007, p. 287). The two surveys in this case study were assumed to be independent of each other.

3.6.2 Testing Research Question 2:

What is the level of agreement between the erosion severity categories measured in the sampled 1:10,000 scale LUC survey, as compared to the same extent in the national 1:50,000 scale NZLRI LUC survey

Spearman's Ranked Correlation Coefficient

A Spearman's ρ was also estimated in the second research question of this case study. This test was used to identify associations in consistency of surveyor judgment in erosion survey measurements between the two LUC surveys.

Accuracy Assessment

An accuracy assessment was performed on erosion severity categories measures in the sample and reference datasets. The comparison involved developing an error matrix (sometimes referred to as a confusion matrix), which in effect is a contingency table. The matrix identified the error in classification between the two surveys. This error is seen in two forms: error of omission and/or error of commission (Congalton & Green, 1999). A commission error happens when an area is included in a sample map, which the reference map states should be a different classification. An omission is the opposite, where an area was excluded from a specific classification in the sample map when according to the reference map, it should have been included.

An overall accuracy statistic was produced in this case study using the following expression:

$$D/N * 100 \tag{3.2}$$

where D = the total number of correct cells along the diagonal axis of the error matrix and N = the total number of cells in the error matrix (Congalton, 1991). This assessment provides a measure of overall agreement between the two LUC surveys. Congalton (2008b, pp. 56-57) explains that an overall accuracy level of 85% is a common standard in accuracy assessments. This standard was used in this study.

Individual class accuracy was also assessed. This was obtained by calculating the Producer's and User's accuracy (Story & Congalton, 1986). Producer's accuracy indicates the probability of a cell value in the sample map being the same as the reference map; that is, it identifies whether the correct erosion severity category is annotated in the sample LUC survey when compared to the reference LUC Survey. This is a measure of omission error. This is expressed in the following equation:

$$x_{ii}/x_{+i} * 100 \tag{3.3}$$

where x_{ii} = the total number or correct cells in a category and x_{+i} = the sum of cell values in the column (Congalton & Green, 1999).

User's accuracy looks at the probability of a cell from the reference map being the same as the sample map, a measure of errors of commission. The following equation represents user's accuracy:

$$x_{ii}/x_{i+} * 100 \tag{3.4}$$

where x_{ii} = the total number or correct cells in a category and x_{i+}= the sum of cell values in the rows (Congalton & Green, 1999).

The Kappa coefficient, which was first proposed by Cohen (1960), was calculated to determine if the difference between the reference map and the sample map was significant. The KHAT$(\widehat{K})$ statistic (Equation 3.5) is another measure of agreement used in this case study. The agreement is based on the actual agreement of the error matrix compared with agreement that might occur by chance (Congalton & Green, 1999, p. 49).

$$\widehat{K} = N \sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r} (x_{i+} * x_{+i}) / N^2 \sum_{i=1}^{r} (x_{i+} * x_{+i}) \qquad (3.5)$$

where r = the number of rows in the matrix, x_{ii}= the total number of correct cells in a category, x_{+i}= the sum of cell values in the column i, x_{i+}= the sum of cell values in the row i, and N = the total number of cells in the error matrix.

Landis and Koch (1977) proposed the following levels of significance for the Kappa statistic or KHAT: $40 \leq \widehat{K} \leq 60$ = moderate agreement; $60 \leq \widehat{K} \leq 80$ = substantial agreement; and $\widehat{K} \geq 80$ = good agreement. The KHAT analysis is similar to the Chi-square analysis (Congalton, 2008a, p. 105).

Chapter 4 Results: Sherry Catchment Case Study

4.1 Introduction

This chapter describes the results of a case study conducted in the Sherry River catchment, located in the Tasman District of NZ. The case study investigated the feasibility of using a geomorphic parameter known as the Melton ratio, calculated through GIS debris-flow modelling, for assessing erosion severity in river catchments. This case study also sought to quantify the measure of spatial uncertainty of observed local-level LUC map units and measured variables as compared with coarser regional-level spatial resolution LUC map units which were used as the underlying data of MFE's proposed ESC system.

4.2 Methodology

4.2.1 Investigating Research Question 1:

What is the level of agreement (association) between the Melton ratio of REC order one polygons and erosion severity measurements of LUC areal map units, generalised at spatial map scales of 1:50,000 or 1:10,000

The aim of the Sherry River case study was twofold. The first was to investigate the relationship of the Melton ratio (Melton, 1965), an index of basin ruggedness and a known debris-flow discriminating parameter (de Scally & Owens, 2004; Irvine, 2011; Watts & Cox, 2010; Welsh & Davies, 2011) with erosion severity identified during LUC surveying at a local map scale of 1:10,000 and a regional scale of 1:50,000. Having an independent identifier of erosion severity would allow an accurate GIS assessment across all of NZ and provide an efficient model for erosion management decision making Most importantly, allowing decision makers the ability to make informed decisions on identifying an adequate spatial resolution for local level LUC erosion surveying.

Realization of the Sherry Catchment Case Study Dataset

Figure 4.1 illustrates the model developed for the realisation and automation of the spatially weighted dataset containing erosion severity and the Melton ratio of both the NZLRI and Tasman LUC surveys. This model was used to complete the thesis objectives and was primarily used in testing research question one, which tested the correlation of the Melton ratio and LUC erosion severity. The model was constructed using the GIS platform ArcGIS 10 (ESRI, 2011). The purpose of this model was to automate a process which first identifies the REC AOIs in both LUC surveys. The NZLRI LUC survey had previously been clipped using the *Clip* tool in the *Data Management Toolset* of ArcGIS 10 (ESRI, 2011) to the Tasman LUC survey; thus, defining the Sherry Catchment Study area and providing equal areas of assessment. The AOIs were then realised by clipping the LUC surveys to the REC order one polygons. The product, two vector polygon layers of their respective LUC surveys, were then rasterised twice, once by the erosion severity attribute and the other by the Melton ratio attribute, at a 10 m resolution, ending with four raster layers at that point of the model. Each LUC survey raster layer was then converted to a point vector layer and then intersected. The *Intersect* tool relates the X and Y coordinates of both units of interest to a specific point, which was referenced from the centroid of the previously realised 10 m raster cells. This created a layer containing the two units of interest along with two columns of unique identifiers for each point. As just explained, a raster model was used for analysis and then converted to vector. This method was best because it samples the same raster cells used in the hard classification accuracy assessment methodology outlined by Congalton and Green (1999). The vector layer can then be saved as a database file and be brought into the statistical package R (R Core Team, 2012) for analysis. Finally, both LUC surveys were intersected into one dataset. The dataset was then used for further non-parametric statistical analysis.

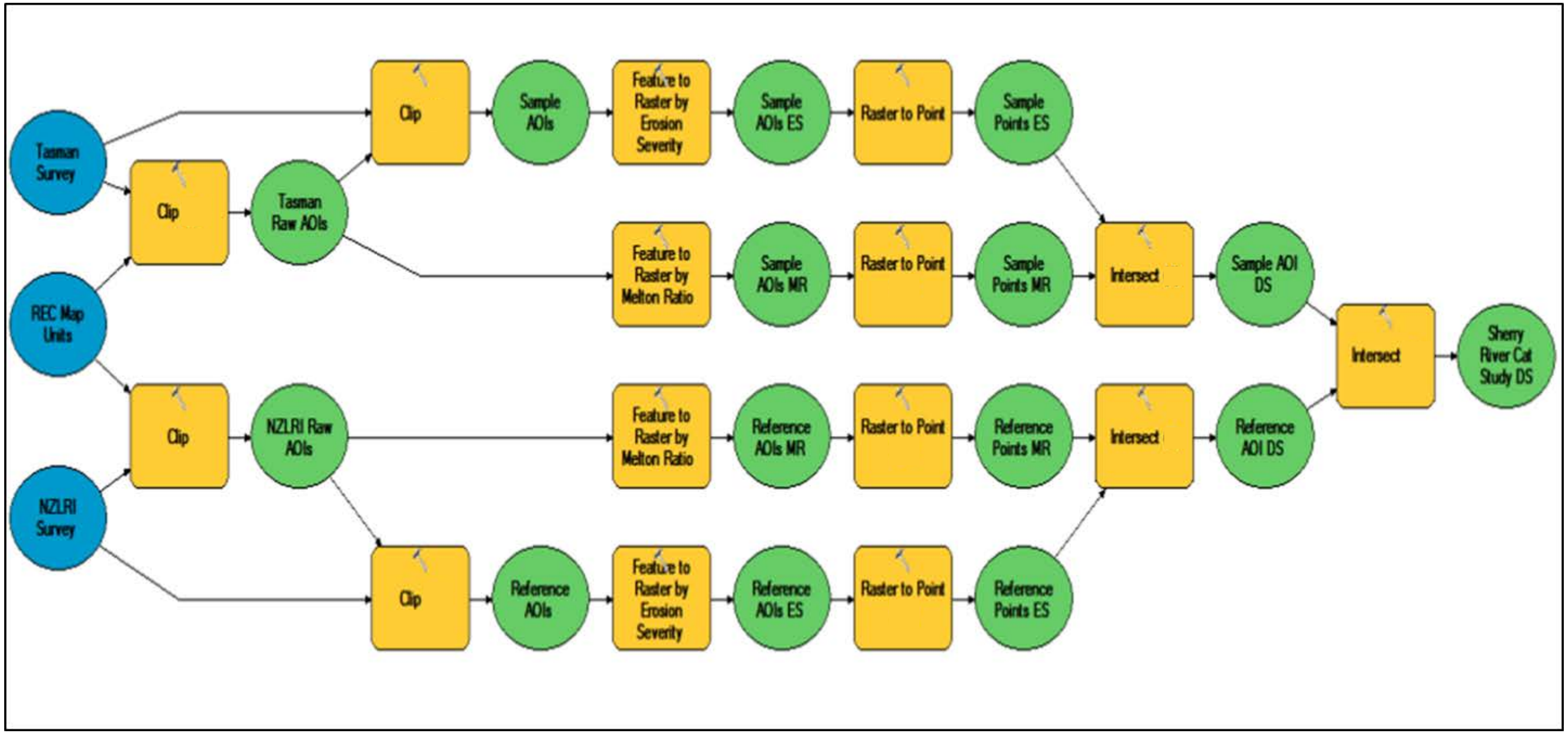

Figure 4.1: ArcGIS model used for the realisation of the Sherry Catchment Case Study dataset.

From the dataset just realised the Spearman's Ranked Correlation Coefficient (Section 3.6.1) was calculated to test the association between the Melton ratio and LUC survey. Two map scales were examined, 1:10,000 and 1:50,000, to explore possible effects of spatial resolution on the association between the LUC survey and the Melton ratio.

4.2.2 Investigating Research Question 2:

What is the level of agreement between the erosion severity categories measured in the sampled 1:10,000 scale LUC survey, as compared to the same extent in the national 1:50,000 scale NZLRI LUC survey

The second aim of the Sherry River Catchment Case Study was to provide an understanding of the degree of spatial uncertainty or the difference between erosion severity values of two LUC surveys, in terms of thematic agreement. Erosion severity values at the regional scale were used to define the underlying data of the four-tier ESC system developed by Bloomberg et al. (2011), and proposed in the revised NES for Plantation Forestry (MFE, 2011c, 2011d). A statistically significant agreement between the two LUC survey's erosion severity category values would suggest that the ESC system, derived from regional data, is able to fulfil its intended purpose in erosion management at a local level. If there is a substantial difference between LUC map units studied in this thesis, then further research is needed to determine the appropriate spatial resolution for erosion severity classifications suitable for use at a local scale.

4.2.3 Accuracy Assessment Model

An accuracy assessment was produced for the Sherry River Catchment Study to examine the second research question, which looked at spatial uncertainty derived from resolution. The accuracy assessment in this case study began with clipping the units of interests to the reference and sample AOIs as explained in Section 3.5.2. Figure 4.2 illustrates the GIS model used to create a combined raster, which contains the values used for the error matrix, also explained in Section 3.5.2.

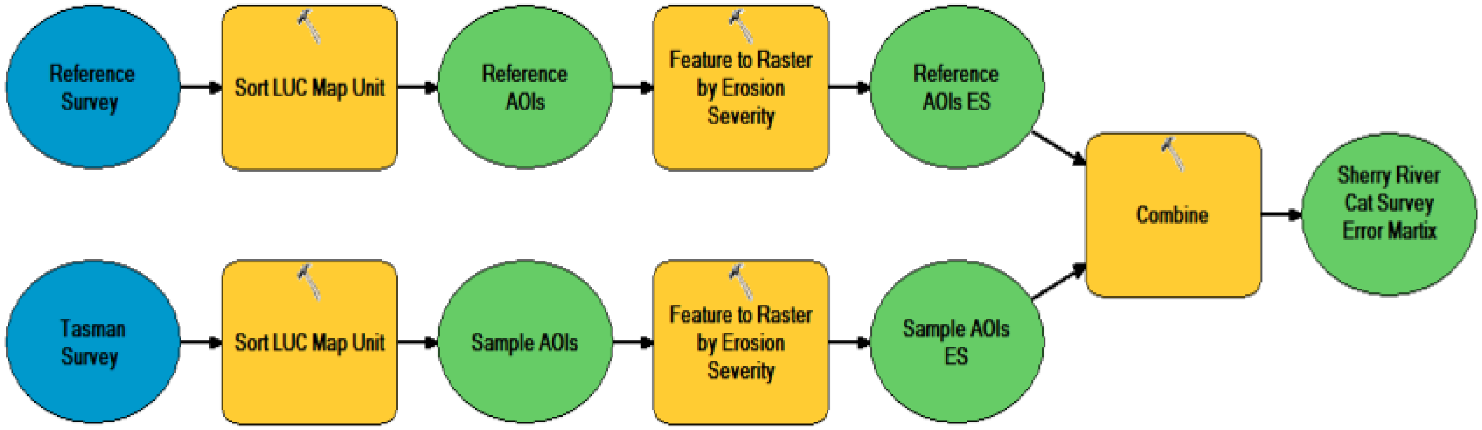

Figure 4.2: ArcGIS model used in the accuracy assessment of this case study. It combines the rasterised polygons of both LUC surveys and its output feature was used in the development of the error matrix.

Cohen's (1960) Kappa coefficient was also calculated to determine the significance of chance agreement in this case study (See section 3.5.2).

4.3 Results

4.3.1 Research Question 1: Associating the Melton ratio and LUC surveying

Contingency Table

Table 4.1 shows the frequencies of sampled erosion severity values per AOI (GIS calculated Melton Ratio) from the Tasman and NZLRI LUC surveys. If there is no association between the Melton ratio for each AOI and erosion severity, then the areas classified as erosion severity 0, 2 and 3 should vary randomly with respect to the Melton ratio values for each AOI. The data in Table 4.1 show no clear association between Melton ratio and erosion severity as further illustrated in the following paragraphs.

Table 4.1: Total Area (m^2) Classified by the Melton Ratio and Sample and Reference LUC Survey Erosion Severity Categories.

Drainage Name (AOIs)	**Sample (Tasman) LUC Survey**					**Reference (NZLRI) LUC Survey**				
		Erosion Severity					*Erosion Severity*			
	Melton R	**0**	**2**	**3**		*Melton R*	**0**	**2**	**3**	
A	*0.511*	494	2613	1306		*0.511*	139	1980	2294	
B	*0.524*	205	3302	2082		*0.524*	9	1713	3867	
C	*0.529*	910	638	2311		*0.529*	119	0	3740	
D	*0.535*	454	2522	507		*0.535*	135	2308	1040	
E	*0.542*	367	1678	1528		*0.542*	252	0	3321	
F	*0.549*	328	1301	1026		*0.549*	188	0	2467	
G	*0.554*	92	1260	3122		*0.554*	0	1109	3365	
H	*0.589*	35	1513	1512		*0.589*	85	0	2975	
I	*0.593*	0	0	2290		*0.593*	0	0	2290	
J	*0.610*	0	0	479		*0.610*	0	0	479	
K	*0.636*	0	0	989		*0.636*	0	0	989	
L	*0.732*	425	716	486		*0.732*	436	1139	52	
M	*0.867*	112	1274	385		*0.867*	479	1030	262	
	Total Area (m^2)	**3422**	**16817**	**18023**	**38262**	**Total Area (m^2)**	**1842**	**9279**	**27141**	**38262**
	Total Area (m^2)	**9%**	**44%**	**47%**	**100%**	**Total Area (m^2)**	**5%**	**24%**	**71%**	**100%**

Figure 4.3 and Figure 4.4 show the median, interquartile, and extreme ranges of the Melton ratio, as the function of the Tasman and NZLRI LUC erosion severities, respectively. The boxplots illustrate no clear relationship between the Melton ratio and the LUC erosion severities. In fact, some AOIs with very high Melton ratios have large areas classified by the NZLRI LUC as having low erosion severity (class = 0) (Figure 4.4).

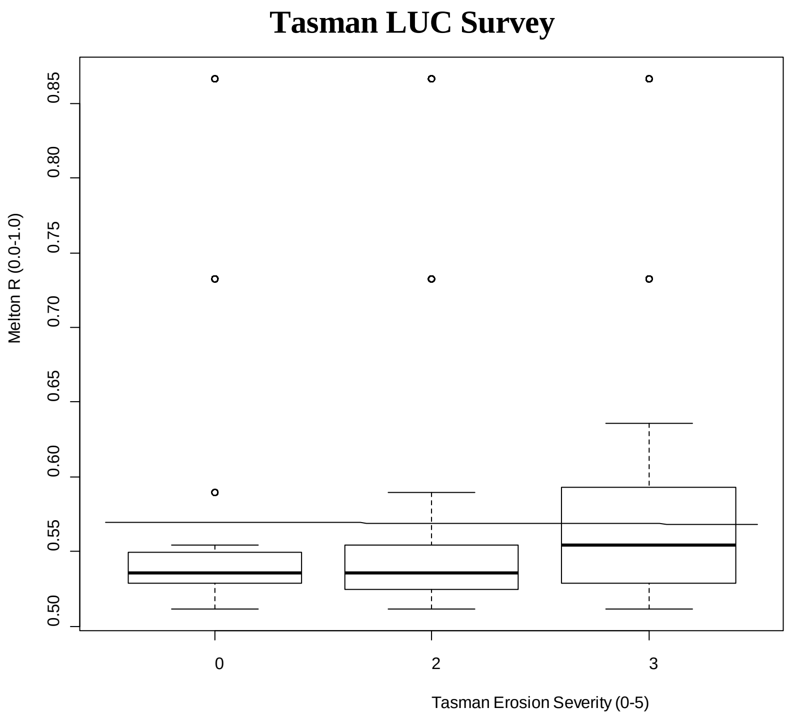

Figure 4.3: Boxplot of the Tasman LUC surveys Melton ratio as a function of the reported erosion severity with a fitted linear model.

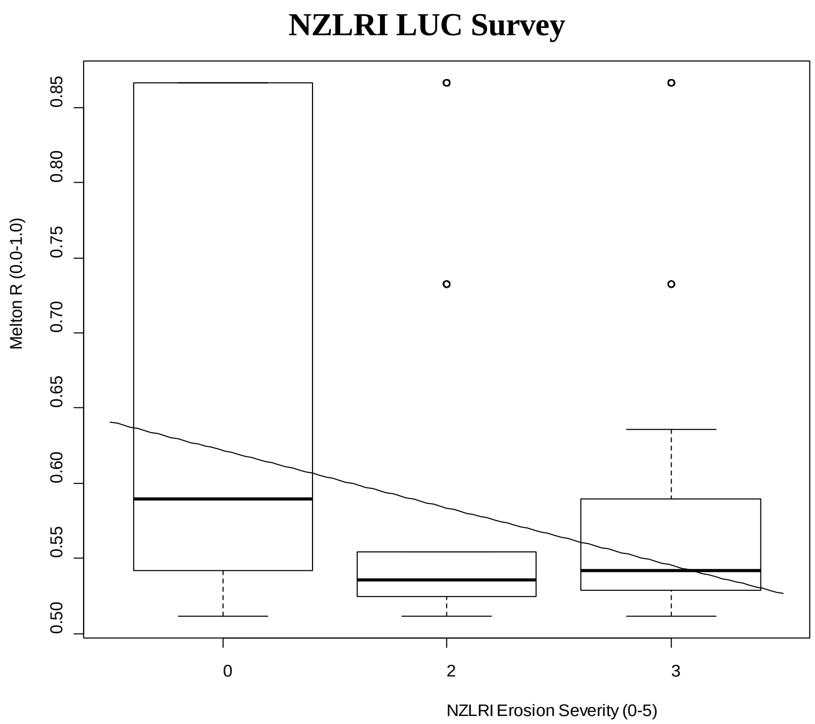

Figure 4.4: Boxplot of the NZLRI LUC surveys Melton ratio as a function of its correlated erosion severity, with a fitted linear model.

Spearman's Rank Correlation Coefficient

The Melton ratio was weakly associated with the Tasman LUC survey's erosion severity ($\rho = 0.193$, with p-value < 0.001). This corresponds to what is shown in Figure 4.3.

The Spearman's ρ for the NZLRI LUC survey, with the Melton ratio vs. erosion severity, was $\rho = -0.004$, with a p-value = 0.460. There is negligible association between the Melton ratio and NZLRI LUC erosion severity, due to the Spearman's ρ being close to 0. This negative trend is shown in Figure 4.4.

Overall, the weak association shown by both Spearman's ρ and Figures 4.3 and 4.4 mean that there is little evidence that shows an association between the Melton ratio and erosion severity.

4.3.2 Research Question 2: Testing Spatial Thematic Accuracy

Spearman's Rank Correlation Coefficient

The Spearman's ρ was calculated to understand the correlation, that is, the consistency of reported erosion severity between the NZLRI and Tasman LUC surveys ($\rho = 0.562$, p-value < 0.001). The test assumed independence of assessment between the two LUC surveys. The ρ value from this model shows a moderate relationship between the two surveys; that is, there is a degree of consistency between erosion severity measurements by the assessors of the Tasman LUC survey and the assessors of the NZLRI LUC survey. Thus we can reject the null hypothesis, that there is no agreement between the erosion severity categories measured in the sampled 1:10,000 spatial resolution LUC surveys, as compared to the same extent in the national 1:50,000 spatial resolution NZLRI LUC survey. However, the agreement between the two surveys can be further quantified using an accuracy assessment.

Accuracy Assessment

The overall accuracy of erosion severity, calculated as explained in Section 3.6.2, when comparing the sample Tasman LUC survey to the referenced NZLRI LUC, was 69%. This outcome identifies poor agreement between the two LUC surveys. The error matrix seen in Table 4.2 shows the numbers of co-registered 10 m pixels from both LUC surveys. Table 4.3 summarises the analytical statistics of the accuracy assessment conducted in this case study which demonstrate a moderate but not significant correlation (i.e., ≥ 85%) between the two LUC surveys. The Producer's accuracy shown in Table 4.3 shows an overall accuracy of 69%, less than the accepted threshold of 85% Congalton (2008b, pp. 56-57). Only erosion severity category 2 had a good overall classification (i.e. 82%). However, when looking at the User's accuracy only 45% of samples with erosion severity 2 in the Tasman LUC survey were correctly classified when compared to the referenced NZLRI LUC survey. The ability of the sample map to predict erosion severity 3 was high, showing a 97% User's accuracy.

Table 4.2: Error Matrix of NZLRI Erosion Severity as Compared to the Erosion Severity of the Tasman LUC Survey per AOI.

		Reference (NZLRI)							
		0	**1**	**2**	**3**	**4**	**5**	**Total**	**% Area**
Sample (Tasman)	**0**	1288	0	1088	1046	0	0	**3422**	**9%**
	1	0	0	0	0	0	0	**0**	**0%**
	2	554	0	7589	8674	0	0	**16817**	**44%**
	3	0	0	602	17421	0	0	**18023**	**47%**
	4	0	0	0	0	0	0	**0**	**0%**
	5	0	0	0	0	0	0	**0**	**0%**
	Total	**1842**	**0**	**9279**	**27141**	**0**	**0**	**38262**	
	% Area	**5%**	**0%**	**24%**	**71%**	**0%**	**0%**		**100%**

The Kappa coefficient was also calculated, ($\hat{K}$ = 44%). This outcome only just exceeds the lower bound of the range for moderate agreement when using Landis and Koch's (1977) labels of strength of associated agreement.

Table 4.3: Overall, Producer's, And User's Accuracy of the Comparison of Erosion Severities of the NZLRI And Tasman LUC Surveys.

Erosion Severity	Producer's Accuracy	User's Accuracy		
0	70%	38%		
1	0%	0%	**Overall Accuracy =**	**69%**
2	82%	45%	**$\hat{K}$ =**	**44%**
3	64%	97%		
4	0%	0%		
5	0%	0%		

Figure 4.5 is the output of a GIS analysis that shows the magnitude of the difference between erosion severity values for the NZLRI and Tasman LUC surveys. A substantial difference in erosion severity between the two LUC surveys is shown by the green and red-coloured areas in Figure 4.5. This indicates that in some areas the Tasman LUC survey

overestimated erosion severity relative to the NZLRI LUC survey, and in other places the opposite was true. This is driven by the heterogeneity of the LUC units between the two LUC surveys (Figure 4.6). For example, in Figure 4.6 the NZLRI LUC unit 7e25 (erosion severity 3) contains significant areas mapped as class 6e18 (erosion severity 2) in the Tasman LUC.

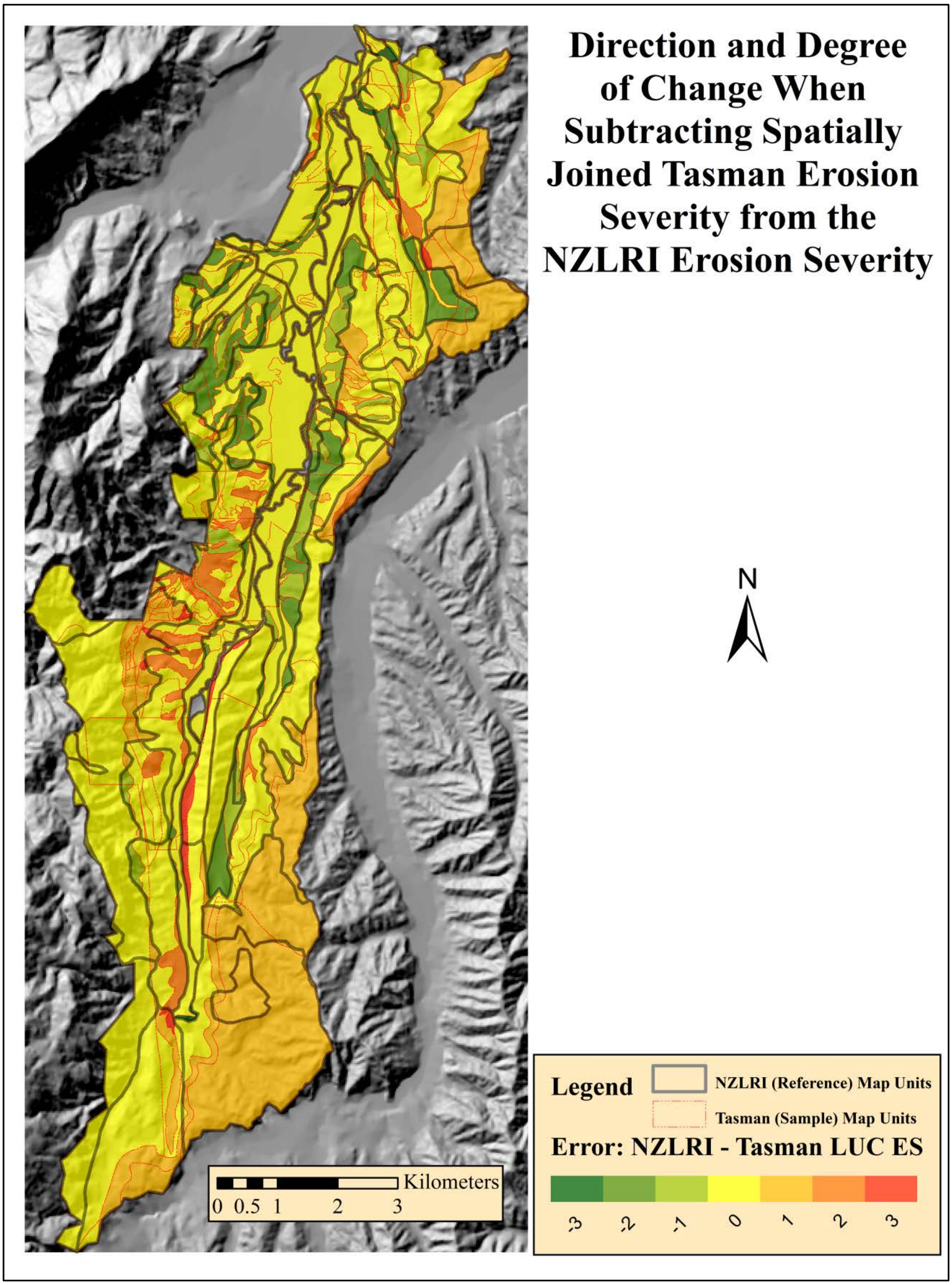

Figure 4.5: Map of the degree and directional change in NZLRI erosion severity when subtracting the spatially joined erosion severity from the Tasman LUC survey.

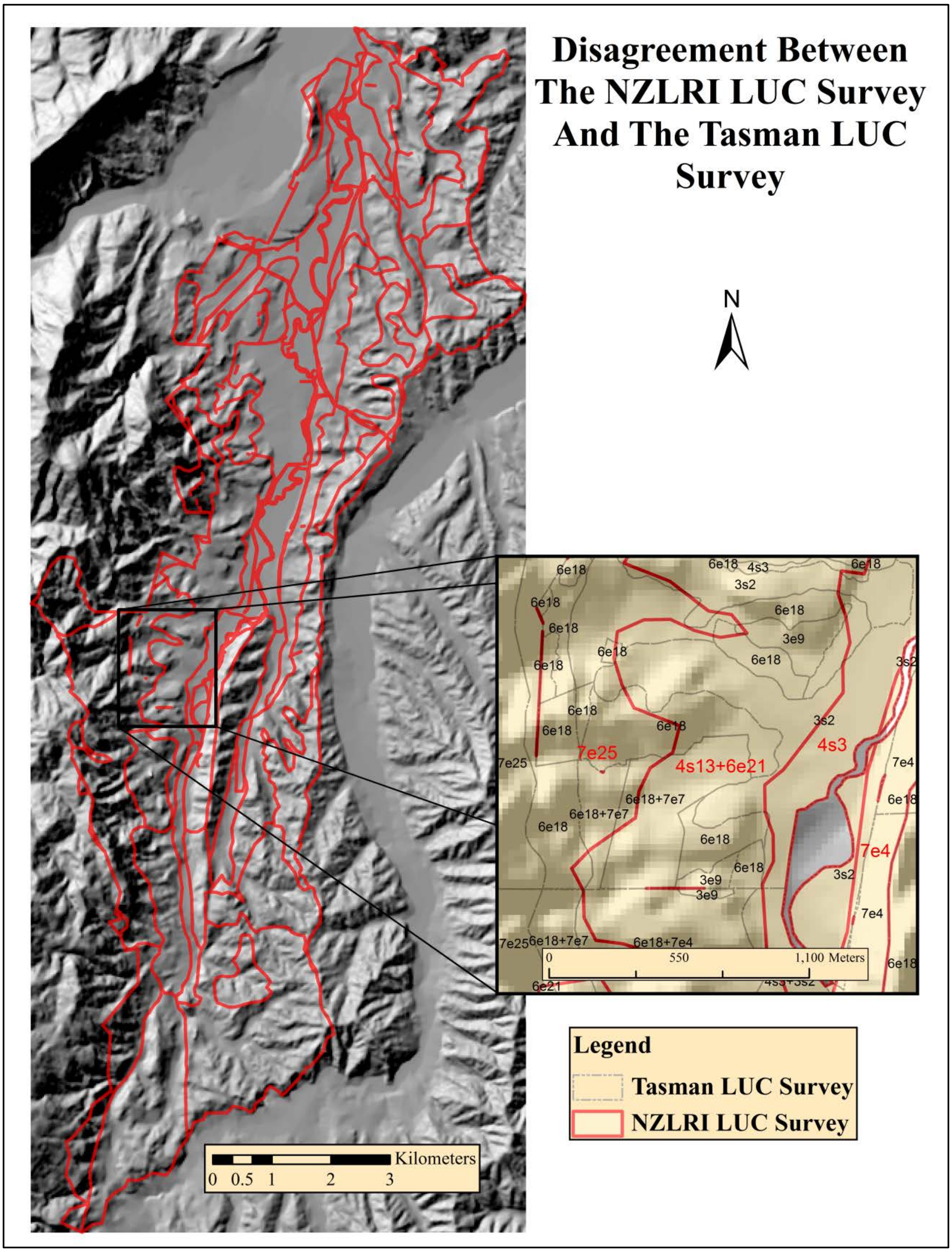

Figure 4.6: Map illustrating the difference between erosion severity map units of the NZLRI and Tasman LUC survey.

4.4 Discussion

When looking at soil variability, a discriminating factor in erosion severity analysis, the finer the resolution the more accurate the survey (Hennings, 2002). The same principle holds with erosion surveying. It is commonly recognised in earth sciences, that the observation scale influences the outcome of analysis (Cocklin et al., 1997, pp. 29-39).

The Sherry River Catchment Case Study looked at the relationship between the Melton ratio ≥ 0.50 of REC order one polygons and the spatially corresponding LUC erosion severity, annotated in both the Tasman and NZLRI LUC surveys of the Sherry River catchment area. A monotonic relationship between the Melton ratio and erosion severity could improve the predictability of erosion in drainage areas, as well as reduce costs of erosion surveying and planning, through the use of currently catalogued environmental data. If a monotonic relation existed, the Melton ratio could also be used as an independent testing variable for erosion severity. This case study also investigated the differences between the erosion severity measurements of the NZLRI and Tasman LUC surveys.

4.4.1 Research Question 1: Association betwen the Melton ratio and LUC survey

The contingency table presented in Table 4.1 showed a substantial relationship between the Melton ratios of AOIs J, K, and L with LUC erosion severity. Drainages with a Melton ratio ≈ 0.6 appear to be the only response variable that can predict erosion severity. However, this is most likely due to the three AOIs having small areas, thus offering little chance of multiple LUC map units covering the AOIs area.

A test for a monotonic relationship between the dependent variable Melton ratio and the independent variable erosion severity using the Spearman's ρ showed negligible relationship between the variables in either LUC survey. The Tasman LUC survey did show a slight positive relationship (ρ = 0.193), while the NZLRI LUC survey showed a very small negative slope (ρ = 0.004), denoting no relationship with the Melton ratio. Nonetheless, the Tasman LUC surveys Spearman's rho was ρ = 0.192; implying a slight but most likely not significant relationship given the autocorrelation present in this study. This result is probably due to the Tasman LUC survey having more polygons per AOI, thus having a higher probability of assignment of more than one erosion severity classes per AOI. The negative ρ of the NZLRI LUC survey is approximately 0, indicating no relationship.

The boxplots shown in Figure 4.3 and Figure 4.4 indicate that the use of the Melton ratio does not effectively predict erosion severity. However, this is expected due to the presence of spatial autocorrelation of the explanatory variable, Melton ratio. Performing spatially explicit analysis such as geographically weighted regression (GWR) or Bayesian conditional autoregressive (CAR) modelling could possibly account for these factors, producing more accurate estimates of the relationships between individual erosion severity categories relative to their proximity to neighbouring map units.

It may be possible to calibrate the Melton ratio to erosion severity by redefining the AOIs. This can be done by intersecting the REC river catchments to the LUC polygons and calculating the Melton ratio by LUC polygon. This operation would investigate the probability of debris-flow being at the borders of LUC map units within any given watershed, rather than the current REC Debris-flow model, which estimates debris-flow at the fluvial fan head.

4.4.2 Research Question 2: Testing Spatial Thematic Accuracy

The Tasman LUC survey had more polygons per AOI than the NZLRI, thus having a higher probability of assignment of more than one erosion severity classes per AOI by the surveyor. The medians shown in Figure 4.3 and Figure 4.4 identify there was a difference in classification of erosion severity between LUC surveys of different spatial resolutions

A Spearman's ρ was evaluated for the AOIs of this case study to examine the second research question, using the erosion severity values in both LUC surveys. The outcome was ρ = 0.648, which signifies a moderate relationship between the two LUC surveys. This implies there was a positive correlation between the assessors of erosion severity categories of the NZLRI and Tasman LUC surveys; providing evidence of low surveyor bias. As the NZLRI erosion severity values went up at any given location, so did the Tasman LUC survey's erosion severity values at the same location.

An accuracy assessment was conducted for this case study, in order to understand the degree of agreement registration of classes between the NZLRI LUC survey (the reference map) and the Tasman LUC survey (the sample map). The overall accuracy was found to be 69% with a $\widehat{K} = 44\%$. This indicates a marginal agreement, yet not significant according to the parameters of this case study. Table 4.3 illustrated marked differences in accuracy between individual erosion severity classes, when looking at the Producer's and User's accuracy. The results from Table 4.3 were consistent with the boxplots illustrated in Figure 4.3 and Figure 4.4.

The empirical methodology used for developing LUC map units and the subsequent surveying of erosion severity measurements will always provide a degree of confounding results when attempting to compare two LUC surveys (due to the nature of human empirical judgement). Notwithstanding, this case study provided evidence that spatial resolution is associated with spatial disagreement in LUC surveys conducted at 1:10,000 and 1:50,000 map scales. The evidence provided in Figure 4.5, the degree and direction of change in erosion severity recorded in the NZLRI LUC survey, along with the outcomes of the accuracy assessment, further demonstrate that it is reasonable to believe that the scale at which the surveyor described erosion severity is a likely casual factor of change between LUC surveys. However, to fully understand the cause and effect between surveyor category selection and the spatial resolution of a LUC survey, two or more surveys need to be conducted by the same surveyors at multiple scales.

4.5 Conclusions

To answer the first research question: There was no significant relationship between the Melton ratio ≥ 0.50 calculated using the REC Debris-flow model and erosion severity values in either the NZLRI LUC survey or the Tasman LUC survey. Using the Melton ratio as a predictor for erosion severity is not recommended when using the parameters set in the Sherry Catchment Case Study.

To answer the second research question: There was significant agreement between the NZLRI LUC survey and the Tasman LUC survey when compared by their respective erosion severities within the 13 AOIs of the Sherry River Catchment Study. The strength of the monotonic relationship presented in this case study ($\rho = 0.648$), demonstrates a consistency in surveyor judgment between the NZLRI and Tasman LUC survey erosion severities.

This suggests that the difference in erosion severity spatial agreement may be due to the spatial resolution of attribute measurement. The degree of disagreement was substantiated by:

1. 69% overall accuracy, which is 16% below the acceptable level;
2. A $\widehat{K} = 44\%$, which only just exceeded the lower bound of the range for moderate agreement; and
3. The low correlation of Producer's and User's accuracies of individual erosion severity categories.

Chapter 5 Results: Horizons Case Study

5.1 Introduction

This chapter describes the results of a case study conducted in the Manawatu-Wanganui Region, located in the North Island of NZ. This case study sought to understand the uncertainty between erosion severity measurements of two LUC surveys produced at different spatial resolutions.

As explained in Chapter 1 and further illustrated in Chapter 4, the MFE recently released a proposed NES for plantation forestry (MFE, 2011d) that contains an ESC system, which used the NZLRI survey for rendering the ESC dataset (Bloomberg et al., 2011). According to the NES for Plantation Forestry, the ESC system will be used for farm level consents and notification purposes (MFE, 2011d, p. 13). The current map scale of the underlying data (i.e., 1:50,000) may be too coarse of a spatial resolution for the ESC's intended purpose; thus, quantifying agreement with a higher resolution dataset may be necessary. An example of a situation, where coarse underlying data of the proposed ESC system would be a hindrance, is when a plot of land having a high ESC rating (ESC class red or erosion severity category 4 or 5), which requires land managers to file a consent for certain activities such as mechanical preparation of land or re-planting activities. Yet, if classified at a 1:10,000 map scale the same plot of land is interpreted as moderate ESC class (ESC class orange or erosion severity category 3), which only requires a notification before such activities. Figure 5.1 further illustrates this possibility by overlaying LUC map units of 1:10,000 scale surveyed by Horizons Regional Council, and the same extent of the NZLRI LUC survey. Figure 5.1 shows the heterogeneity of the map units and their erosion severity measurements from both LUC surveys.

Heterogeneity of Erosion Severity Values of The Horizons Region Case Study

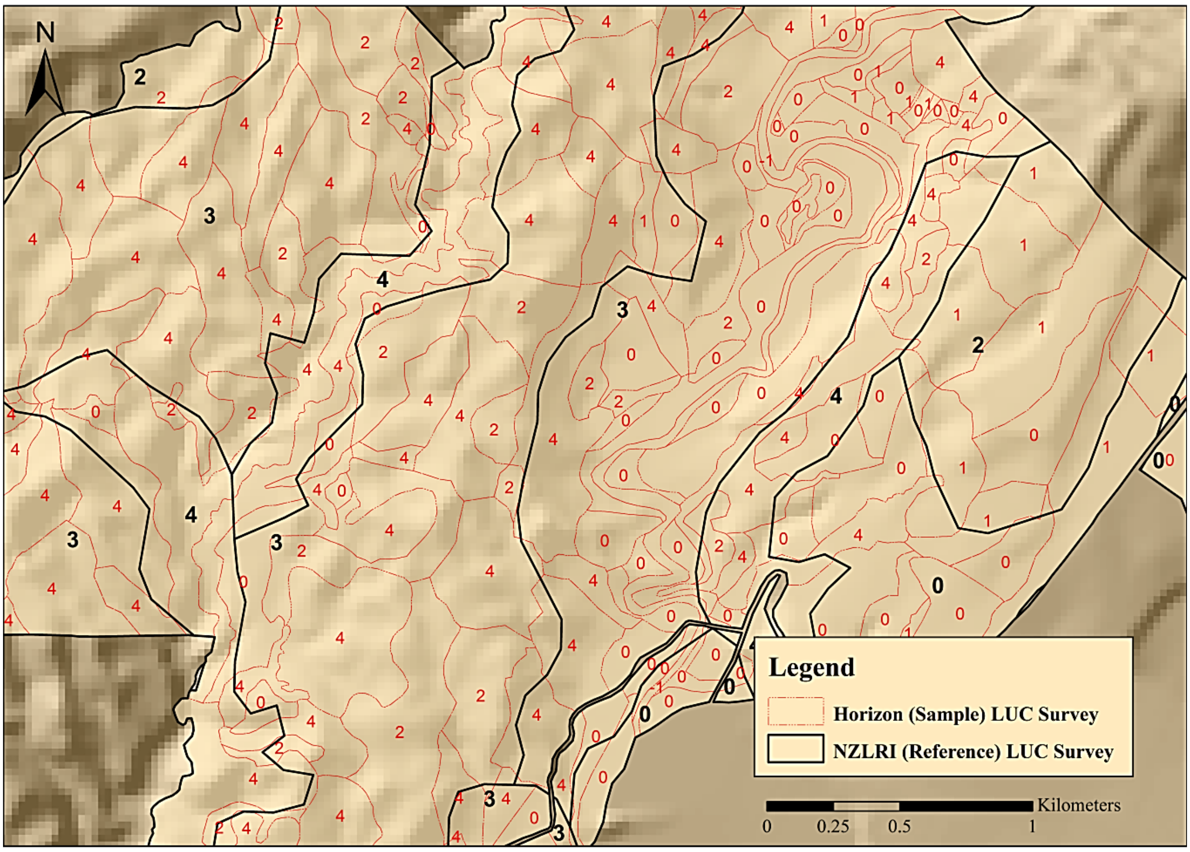

Figure 5.1: A map showing the heterogeneity of erosion severity values between the 1:10,000 scale Horizons LUC survey, as compared to the 1:50,000 scale NZLRI LUC scale.

Often scale dependency of a measured attribute type is overlooked when conducting multi-scale analysis. This is important because the relationship between variables at one scale may go unnoticed or seem distorted when viewed at another spatial resolution (Gotway & Young, 2002). Many land use models are hindered by these potentially erroneous data and often lack adequate validation (Kok et al., 2001). In many situations researchers use the best data available and are faced with the problem of how to best design a decision support system, based on empirically driven integration of physical and environmental parameters (e.g., LUC surveying), often measured at different spatial resolutions (e.g., soil surveys) and with temporal constraints (e.g., vegetation cover assessments may vary markedly over relatively short time spans).

This case study worked under the assumption that in general, quantifiable attributes measured at a finer resolution (1:10,000 map scale) will be more accurate than the same attributes at a coarser resolution (1:50,000 map scale). This is based on the premise that a more accurate measurement of erosion severity can be made within a smaller geographical extent. Spatial data in most cases exhibit an increasing heterogeneity with increasing map scale, which equates to decreased spatial resolution (Longley, 2001, p. 99). This is a common issue with spatial statistics and part of the MAUP (Section 2.6). However, the scale or detail that one uses to represent reality will often determine whether a spatial characteristic will appear regular or irregular (Longley, 2001, p. 98). Thus, in this case study a sampled “fine resolution” survey is used to understand the difference in spatial uncertainty in areal LUC map units and associated erosion severity measurements, when compared to a coarser referenced dataset.

5.2 Methodology

This case study aimed to quantify the thematic agreement between the fine resolution Horizons LUC survey (Todd et al., 2012) areal map units and their erosion severity measurements, as compared to the same units of interest and spatial extent as the coarser NZLRI LUC survey. The datasets were surveyed at map scales of 1:10,000 and 1:50,000 respectively. If there is a strong measure of agreement between the two datasets, then this case study will show that the use of finer resolution underlying data in MFE’s ESC system will have no impact in its current form. If there is a substantial difference, then this study will provide decision makers with a measure of difference between erosion severity measured at local level LUC map units as compared to regional level LUC assessments.

5.2.1 Testing Research Question 2:

What is the level of agreement between the erosion severity categories measured in the sampled 1:10,000 scale LUC survey, as compared to the same extent in the national 1:50,000 scale NZLRI LUC survey

To understand the degree of agreement between erosion severity measurements among the two proposed LUC surveys, the above research question was investigated. This question assumed independence of assessors. This case study assigned the NZLRI LUC survey as the reference survey, while the Horizons LUC survey was the sample survey. Nonparametric statistical modelling and spatial analyses were performed and are outlined in the following section.

Realisation of the Horizons Case Study Dataset

As with the Tasman LUC survey equal spatial population areas of measurements between the Horizons LUC survey and the NZLRI survey were established using the following procedures and the ArcGIS 10 Desktop (ESRI, 2011).

<u>Data cleaning</u>

The first step in the realisation of the case study dataset was to clean up the data using the same procedure as discussed Section 3.5.

<u>Render spatially comparable AOI geographic extents</u>

The same procedures were used to render comparable AOIs in this chapter, as outlined in Section 3.5 for the realisation of the dataset for testing the Spearman's ρ. Section 4.2.1 of the previous chapter followed the same procedure except that the sample dataset is now the Horizons LUC survey (Todd et al., 2012) and the reference is the same spatial extent as the Horizons yet *Clipped* from the NZLRI LUC survey (Landcare Research, 2002a).

The Horizons LUC survey and the NZLRI LUC survey were used to render an intersecting point layer dataset as outlined in the previous chapter and the methodology chapter; the process illustrated in Figure 5.2.

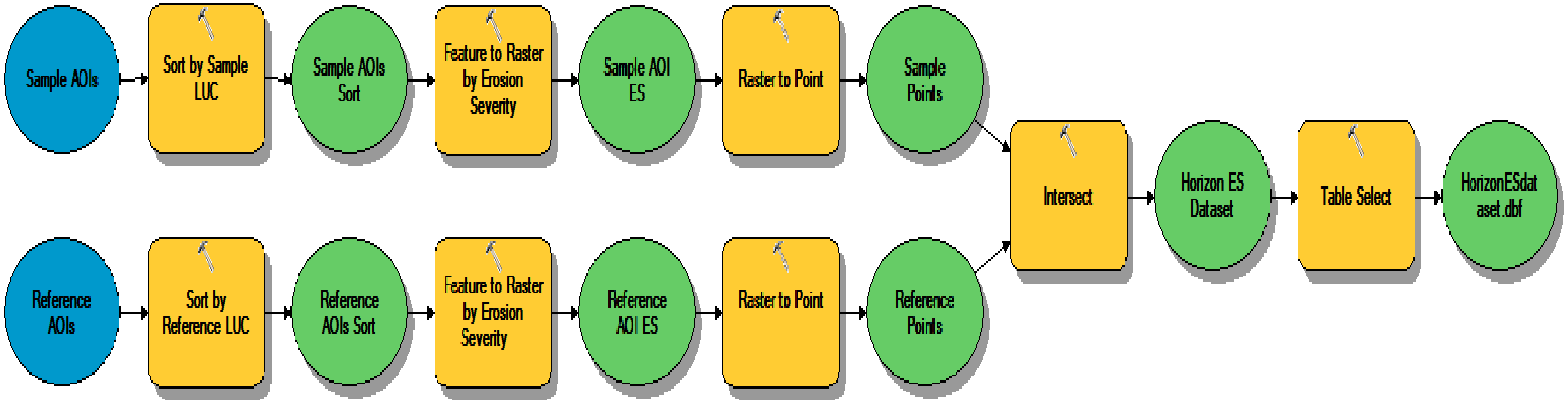

Figure 5.2: ArcGIS model for the realisation of an erosion severity dataset for statistical and spatial modelling.

From the realised dataset the Spearman's Rank Correlation Coefficient was calculated to understand the association between the ranking of erosion severity by the assessors of the sample and reference surveys of the Horizons Case Study.

5.2.2 Accuracy Assessment Model

Figure 5.3 illustrates the GIS model used to render the raster dataset for the Horizons Case Study, which contains the values used in the error matrix needed to calculate the statistics of an accuracy assessment. This model followed the same procedure as outlined in Section 3.5.2 and Section 4.2.2.

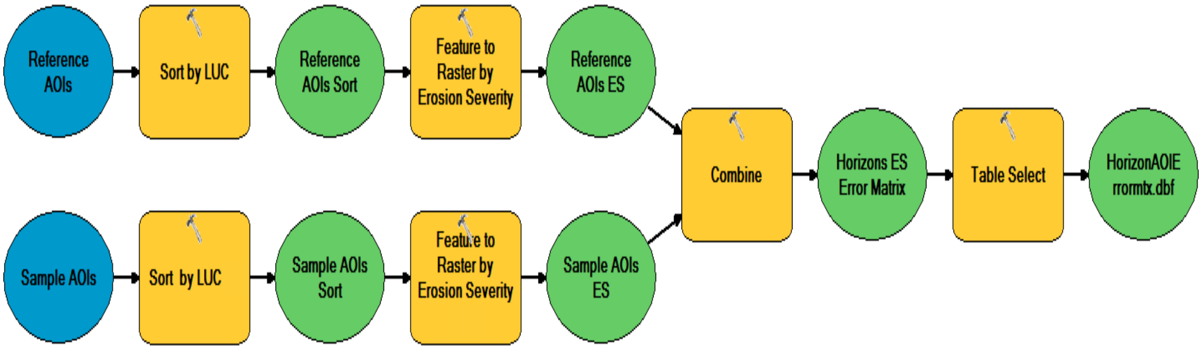

Figure 5.3: ArcGIS model used in the accuracy assessment of the Horizons Case Study.

Cohen's (1960) Kappa coefficient was also calculated to determine the significance of chance agreement in the Horizons Case Study.

5.3 Results

Spearman's Rank Coefficient

The Spearman's ρ was calculated to identify if there was a consistency in measurement between the erosion severity categories in the Horizons LUC survey, when comparing the same unit of interest and spatial extent of the NZLRI LUC survey. In effect, this test was conducted to provide an understanding of whether the surveyors of both LUC surveys were in agreement on the degree of erosion severity measured over the entire spatial extent of the Horizons Case Study. However, this test does not provide a measure of spatial agreement. The Spearman's coefficient for the Horizons Case Study was $\rho = 0.663$ ($\alpha < 0.001$). This indicates a moderately strong monotonic relationship between the erosion severity categories of both LUC surveys and implies there is a correlation in surveyor thematic agreement over the extent of the study area. However, this test does not provide a measure of spatial agreement.

Accuracy Assessment

The intent of the accuracy assessment was to quantify the extent of agreement between co-registered cells when comparing the sample dataset (i.e., Horizons LUC survey) to the reference dataset (i.e., NZLRI LUC survey). Table 5.1 provides the error matrix of the Horizons Case Study accuracy assessment and illustrates the degree of distribution of erosion severity categories when comparing the response variable (Horizons erosion severity) to the dependent variable (NZLRI erosion severity). The sample dataset showed a majority of its area being classed as erosion severity 2, while the reference dataset classed 13% more erosion severity 3 cells. There was no erosion categories of 1 or 5 sampled in the AOI of this case study as illustrated in Table 5.1.

Table 5.1: Error Matrix of Erosion Severity Categories Measured Within the AOIs of the Horizon Region Case Study.

Sample (Horizons)	Reference (NZLRI)	0	1	2	3	4	5	Total	% Area
	0	84562	0	30529	28259	11869	0	**155219**	**21%**
	1	0	0	0	0	0	0	**0**	**0%**
	2	14164	0	207719	110330	5081	0	**337294**	**46%**
	3	1886	0	37286	158014	12959	0	**210145**	**29%**
	4	1022	0	3025	12972	17529	0	**34548**	**5%**
	5	0	0	0	0	0	0	**0**	**0%**
	Total	**101634**	**0**	**278559**	**309575**	**47438**	**0**	**737206**	
	% Area	**14%**	**0%**	**38%**	**42%**	**6%**	**0%**		**100%**

Table 5.2 provides the analytical statistics of the error matrix for the Horizons Case Study accuracy assessment. As depicted in the table, the overall accuracy was calculated at 63%. Given the threshold for agreement set at 85 % accuracy, the answer to the second research question was that there was no significant agreement between the datasets presented. There was good agreement in some of the erosion severity categories over the entire extent of the case study, seen in the high percentages of the Producer's accuracy, ranging from 37-83%. The ability of the Horizons LUC survey to predict the same erosion severity category (User's accuracy) as the NZLRI LUC survey was weaker, ranging from 51-75%. The Kappa statistic was calculated to be $\widehat{K} = 46\%$, signifying moderate agreement according to Landis and Koch (1977).

Table 5.2: Overall, Producer's, and User's Accuracy of the Comparison of Erosion Severities of the NZLRI And Horizons LUC Surveys.

Erosion Severity	Producer's Accuracy	User's Accuracy		
0	83%	54%		
1	0%	0%	**Overall Accuracy =**	**63%**
2	75%	62%	**$\widehat{K}$ =**	**46%**
3	51%	75%		
4	37%	51%		
5	0%	0%		

Figure 5.4 shows the erosion severity categories measured in the Horizons LUC survey as a function of the same unit of interest and spatial position as the NZLRI LUC survey. The line drawn in Figure 5.4 shows the positive trend of the function of the LUC surveys, through the median, interquartile, and extreme ranges associated erosion severity measurements. This figure illustrates how the Horizons LUC survey under-predicts erosion severity in categories 2-4, relative to the NZLRI LUC survey.

Horizons LUC as a Function of the NZLRI LUC Erosion Severity Values

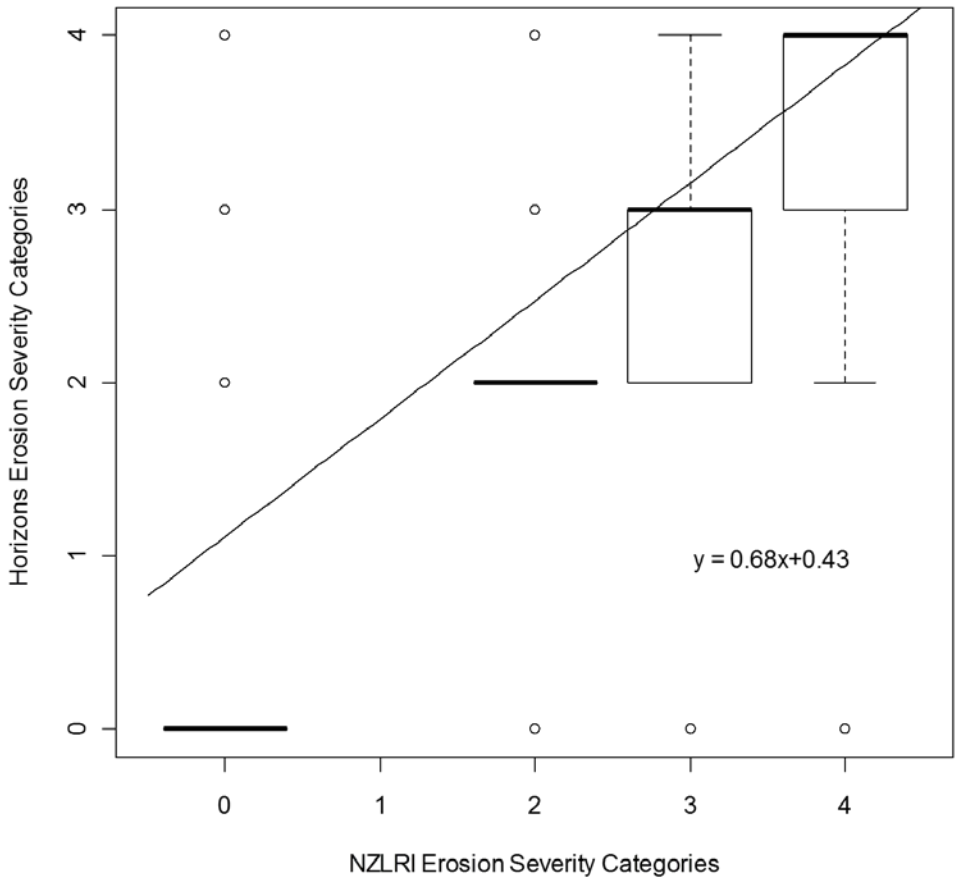

Figure 5.4: Boxplot and linear model of erosion severity categories measured in the Horizons Case Study, where the Horizons erosion severity values were a function of the NZLRI's erosion severity measurements.

Figure 5.5 is a GIS analysis that provides the spatial direction of thematic agreement when subtracting the erosion severity values of the Horizons (Sample) dataset from the reference (NZLRI). This is overlaid with the areal LUC map units to further illustrate the heterogeneity and change in generalised areal units. The thematic colour red indicates that the finer resolution dataset is under-predicting erosion severity in respect to the NZLRI LUC survey, while the colour green indicates an over-prediction. Figure 5.5 also illustrates no apparent consistency in thematic agreement (i.e., showing all one colour) over the broad geographic extent the Horizon Case Study surveyed. However, there appears to be a consistent magnitude of under-prediction of the finer resolution data, as compared to the NZLRI when predicting erosion severity in flat/river beds.

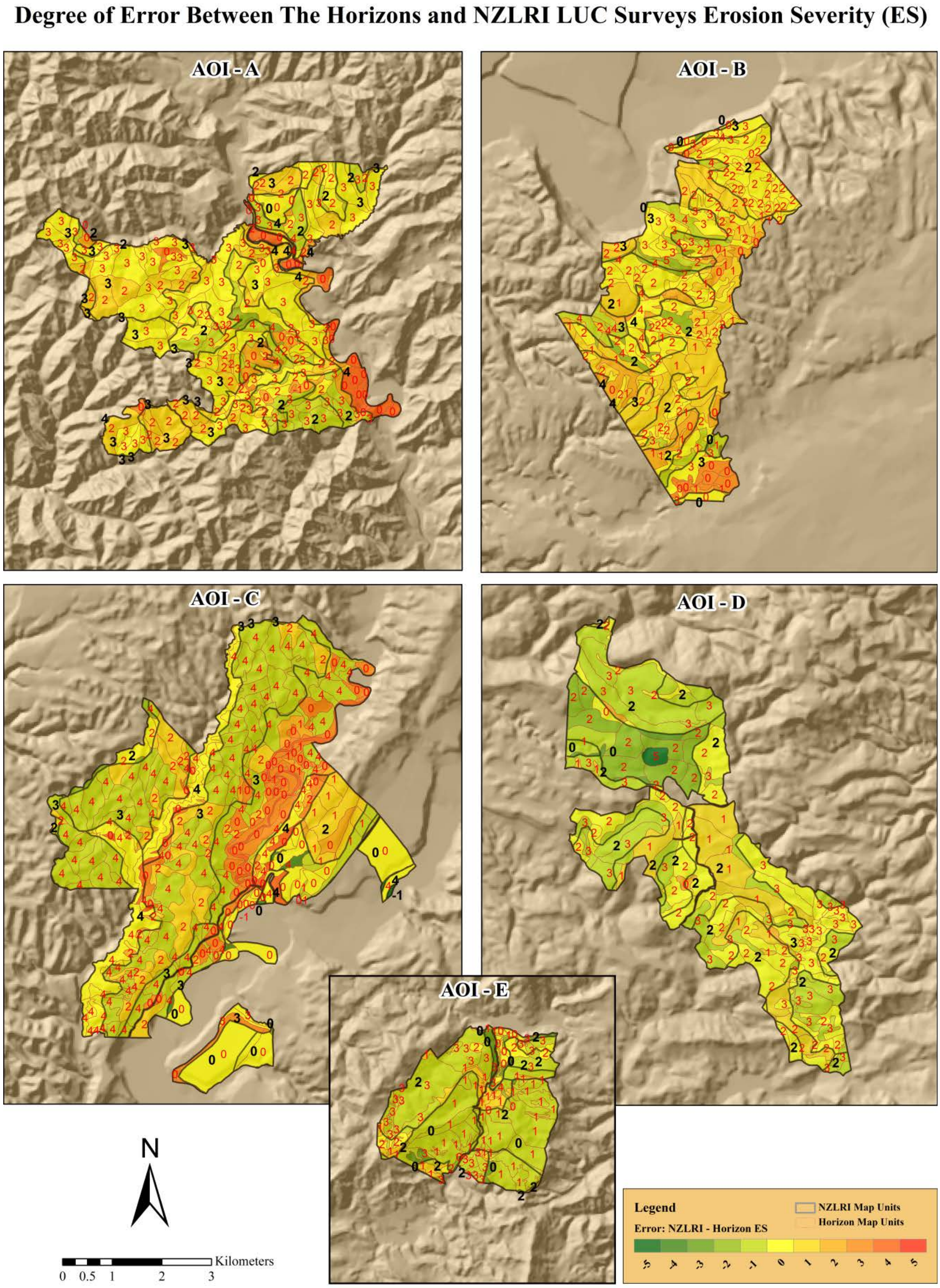

Figure 5.5: Map of the magnitude of difference in erosion severity between the Horizons LUC erosion severity values from the NZLRI LUC erosion severity measurements.

The NZLRI LUC erosion severity values are shown as black digits, the Horizons LUC erosion severity values are shown in red digits. The differences between these are represented by the colour scheme in the map legend.

5.4 Discussion

The Horizons Case Study quantified the measure of agreement between the erosion severity categories of the Horizons LUC survey as compared to the same unit of interest and spatial extent as the NZLRI LUC survey. The Horizons LUC survey was measured at a local 1:10,000 map scale, while the NZLRI LUC survey was measured at a coarser 1:50,000 scale. To investigate the agreement between the Horizons and NZLRI survey the following research question was asked: What is the level of agreement between the erosion severity categories measured in the sampled 1:10,000 scale LUC survey, as compared to the same extent in the national 1:50,000 scale NZLRI LUC survey? An accuracy assessment was also conducted for this case study, in order to understand the degree of co-requisited (matching cells) registration of classes between the NZLRI LUC survey (the reference map) and the Horizons LUC survey (the sample map).

Spearman's Rank Coefficient

The Horizons Case Study tested the two LUC datasets using the Spearman's Rank Coefficient with the intent of understanding the consistency of categorical measurement of erosion severity of the two LUC surveys. The Spearman's ρ was 0.663. This value is moderately strong and indicates there is a consistency of ranking between the two LUC surveys identified in this case study. Over the entire spatial extent of all AOIs identified in this case study, the surveyors were consistent in ranking erosion severity categories, that is, the higher the categorical rank measured in the Horizons LUC survey, the higher the same unit of measure is seen in the NZLRI LUC survey. Given the spatial autocorrelation present and the artificial sampling methodology in this case study, the Spearman's Coefficient statistical power is weakened, in that an unbiased estimate of statistical significance of the p-values is not possible.

Nonetheless, the test is still useful when given knowledge of the context of the case study and the measured variables (erosion severity).

Accuracy Assessment

An accuracy assessment identified the agreement between the two LUC surveys analysed in this case study. Figure 5.1 showed the heterogeneity observed when overlapping the erosion severity values of the Horizons and NZLRI LUC surveys. This accuracy assessment provided a quantitative measurement of agreement between these two surveys. The overall accuracy was calculated to be 63% (Table 5.2). This falls short by 22% compared to pre-set limit for agreement of ≥ 85%. The erosion severity category 0 had a good agreement with 83% (Producer's Accuracy) when looking at erosion severity categories as a whole, yet when looking at User's accuracy (i.e., the ability of the sample map being able to predict the reference map) only 54% of the time was the sample map able to accurately predict the reference map category 0. Erosion severity category 3 had a good individual categorical agreement according to the User's accuracy (75%), yet even this value is 10% below the established significance threshold.

A Kappa statistic, which also provides a measure of agreement and is part of an accuracy assessment (Congalton & Green, 1999), was also calculated ($\widehat{K}$ = 46%) corresponding to moderate agreement according to Landis and Koch (1977).

Figure 5.5 illustrates the directional change in thematic agreement of erosion severity measurements, obtained by subtracting the Horizons LUC erosion severity values from the same units of interest in the NZLRI LUC survey. The differences in size and definition of areal map units are also illustrated when overlapping the two LUC surveys' areal map units (between 2 to >10 Horizons LUC units within each NZLRI LUC unit.

5.5 Conclusion

The Spearman's Rank Correlation Coefficient suggested a consistency in thematic agreement between the surveyors of the two datasets analysed. However, an accuracy assessment illustrated poor spatial agreement between LUC map units and their erosion severity categories in the Horizons LUC survey when compared to the same unit of interest and spatial extent of the NZLRI LUC survey. Therefore, in the context of the Horizons Case Study, there was clear disagreement between erosion severity values measured at a 1:10,000 map scale, as compared to erosion severity measured at 1:50,000 map scale of the same spatial extent. The results providing further evidence which supports the premise that the underlying data used in Bloomberg and others (2011) ESC system is not suitable for the MFE's intended purpose at a local scale.

Chapter 6 Comprehensive Discussion

6.1 Introduction

The key results of the combined case studies of this research are as follows:

1. Evidence has shown negligible association/correlation exists between LUC erosion severity surveying and Melton ratio values calculated using Irvine's (2011) REC Debris-flow model at a local 1:10,000 and regional 1:50,000 spatial resolution in the Sherry River catchment.

2. Substantial overall disagreement was quantified for erosion severity measurements surveyed at the spatial resolutions of 1:10,000 and 1:50,000 in the accuracy assessments conducted in this study.

3. Substantial individual erosion severity categorical disagreement was quantified in the accuracy assessments conducted in this study, which looked at the same variables just mentioned.

This chapter discusses the interpretation of the key results of the case studies provided in Chapters 4 and 5. Implications of this study will be discussed utilising results outlined in Sections 4.3 and Section 5.3.

6.2 The use of the Melton ratio for an independent discriminator of erosion severity and validation tool for quantitative assessment of LUC surveys generalised at different spatial resolutions

6.2.1 Interpretation of Results

Work by de Scally and Owens (2004), Watts and Cox (2010), in addition to Welsh and Davies (2011) has shown that the Melton ratio can predict debris-flow occurrence in most watersheds within NZ. However, this study found the Melton ratio calculated by debris-flow modelling is not well correlated with LUC erosion severity. The lack of association between the two forms of erosion measurement was due to the contrast of mapped areal boundaries, a zoning effect. An attempt was made at correlating a value that represents a whole catchment (REC debris-flow model) with a value that predicts a point location effect (LUC erosion severity). King (1997) would label this an ecological inference problem, due to the attempted use of aggregated data (Melton ratio) to assess individual (erosion severity) data.

The Melton ratio was calculated based on the area of a REC order one polygon and elevation values of a DEM. These calculations were then assigned as one homogenous value for the complete extent of a REC polygon (i.e., watershed or AOI in this study). In contrast, erosion severity was assigned to an areal map unit based on empirical measurements, limited to the extent of LUC areal map units. As previously explained, LUC areal map units are delineated by drastic changes in geomorphic and physical variables; consequently, elevation and/or slope easily become a border parameter. Therefore, LUC map unit boundaries are often located “cross-slope”, as a function of soil, rock, and vegetation changes with elevation, while REC polygons extend downslope from ridge to valley, as a function of a watershed processes.

6.2.2 Potential Improvements to the Methodology

The use of a different debris-flow model, such as Welsh and Davies (2011) model, where the AOIs areal extent can be re-defined to better fit LUC areal map units may improve correlation. As previously explained, the area of a LUC map unit is defined by significant changes of one or more of the primary physical factors inventoried in the NZLRI (i.e., rock type, soil, slope angle, erosion type and severity, and vegetation cover) (Lynn et al., 2009, p. 12), while the area used to calculate the Melton ratio is based on watershed parameters. Given the nature of empirical generalisation of LUC areal map units, there will always be a high probability of multiple map units in any given watershed, due to autocorrelation of natural phenomena (e.g., soil, rock, slope, erosion, and vegetation) spatial distributions, yet there is only one Melton ratio value per watershed. It may be possible to define the extent of the AOIs for correlation measurements of the Melton ratio and erosion severity, by placing “pour points” as explained by Welsh and Davies (2011) at the intersection of LUC areal map units and flow accumulation. The LUC areal map unit boundaries are treated like a house location, which the Welsh model identifies as a hazard. The “pour points” act as a boundary in Euclidean distance and change the shape of a watershed. This method would then re-define watershed areas, changing Melton ratio values, and possibly predicting a closer location of debris-flow in a watershed than other models.

It may also be justified to attempt to modify the debris-flow model used in this study, the REC debris-flow model. The extent of the polygons used in this model hinders correlation with the areal extent of LUC map units. Re-defining these map units to better fit the paradigm of erosion severity analysis is imperative. Therefore, in theory a watershed (REC order 1 polygon) could be ‘cut’ using LUC areal units as the “cookie cutter” and a new Melton ratio calculated for the new areal unit. This operation can be done using ArcGIS 10 (ESRI, 2011) Geospatial Analyst tool *Intersect*, in the *ArcToolbox*. It would be conducive to test the Melton ratio calculated in new areal map units, as seen in Equation 2.1, by using the maximum and minimum elevations of the new polygons, as shown by additional labelled numbers in Figure 6.1 then dividing the elevations of the new polygons by their own areas. It could then be predicted that the steeper upper portions of a watershed, shown in red in Figure 6.1, would contain higher Melton ratio values and a trend of decreasing Melton ratio would be seen as the terrain becomes more even. This value could possibly provide an estimate of locality of debris-flow in a watershed. Normally, the Melton ratio only calculates the probability of a debris-flow occurrence within the whole extent of any given watershed.

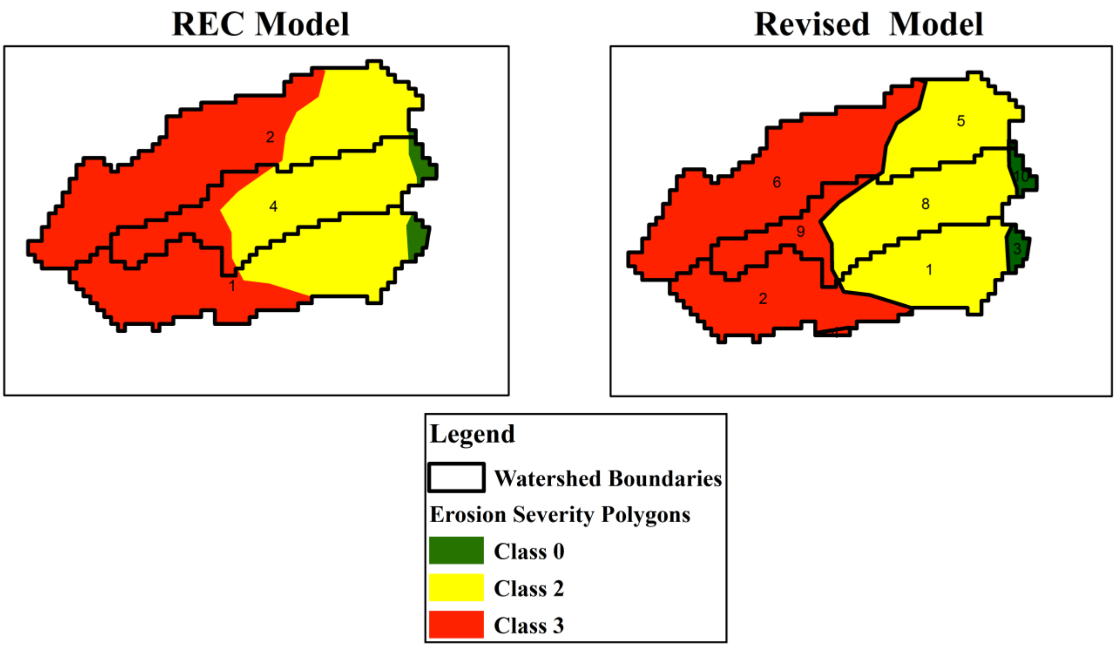

Figure 6.1: Illustration of *Intersect* operation, which would define new polygons for calculation the Melton ratio.

The new polygons are an intersect of REC order 1 polygons and LUC areal map units. The numbers inside the polygons are labels for each individual polygon.

6.2.3 Implications

This study did not find evidence to support a correlation between the Melton ratio and LUC erosion surveying at the spatial resolutions associated with map scales 1:10,000 or

1:50,000. If the Melton ratio were correlated with erosion severity, a clearer quantifiable association could be made between LUC surveys at different spatial resolutions.

6.2.4 Limitations

Time was a major limitation in investigating the first research question. Testing multiple Melton ratio values, in addition to the selected ≥ 0.5 value, would possibly provide a better understanding of the correlation between the Melton ratio and LUC erosion severity measurements in the context of NZ watersheds. This action would provide more AOIs for analysis and reduce autocorrelation effects.

Using other variables in addition to the Melton ratio, such as watershed length and slope, could also prove useful for defining discrete areas and variables for identifying debris-flow as shown by Welsh (2011) and Wilford et al. (2004).

One of the major limitations of this case study was the use of 25 m DEMs. Higher resolution DEMs are becoming increasingly more available due to lower costs and more efficient technologies, such as Light Detection and Ranging (LiDAR) technology (e.g., Wolf, 2011). Higher resolution DEMs would provide different and presumably more correct elevation values to use in the calculation of the Melton ratio.

6.3 Accuracy assessment quantifying spatial uncertainty of empirically generated LUC map units

6.3.1 Interpretation of Results

A hard classification accuracy assessment was chosen to quantify a pair-wise measure of agreement between two LUC surveys, measured at a finer 1:10,000 map scale, as compared to the same extent of coarser areal map units surveyed at a map scale of 1:50,000, from the NZLRI (i.e., the underlying data of the ESC). A hard classification accuracy assessment was used because of time constraints, a well published methodology, and budgeting considerations. Most peer reviewed papers explain that statistical comparison of thematic maps is a difficult process and at present, there is no significantly better method for map comparison (Foody, 2002). Thus, inevitably some degree of accuracy will always be sacrificed for cost (Congalton & Green, 1999). The use of NZLRI LUC data in MFE's proposed ESC system was a product of this process and the subject of this study.

Research suggests that finer resolution mapping will prove a better probability of defining erosion occurrences (e.g., Basayigit & Senol, 2008; Galli et al., 2008; Lin et al., 2005). However, substantial costs are involved in high resolution mapping. Table 6.1 illustrates these costs by listing estimated expenses of soil surveying in NZ by spatial resolution per ha and tabulates rough estimates of what a soil survey would cost, if one was to be conducted across the entire extent of the case studies areas reported in this thesis.

Table 6.1: Estimates of Soil Survey Costs in NZ Dollars (NZD) at Different Spatial Resolutions for NZ, at 2006 Inflation and Exchange Rates.

Resolution	NZD/ha	NZD/Sherry River Cat. Case Study	NZD/Horizons Case Study
1:10,000	$35.10	$215,654.40	$258,827.40
1:25,000	$9.70	$59,596.80	$71,527.80
1:50,000	$3.70	$22,732.80	$27,283.80

(From Manderson & Palmer, 2006)

An accuracy assessment uses an error matrix, often referred to as a confusion matrix, to assess co-registration of erosion severity classified pixels. Openshaw (1984a), who defined the MAUP, used crosstabulations (error matrices) to assess the significance of the MAUP in census data in Italy. Accuracy assessments such as Maingi et al. (2002) and Latifovic and Olthof (2004), use error matrices to provide measures of agreement, much like Openshaw's study. As explained in Section 2.6, the issue of scale (i.e., spatial resolution) has been identified for some time, but it was not until the mid-20th century that researchers started to statistically analyse the problem.

This thesis attempted to understand the effect of changes in map scale on the error, also known as "spatial uncertainty," in the development of areal map units and their associated erosion severity measurements of NZ's LUC surveying system. This thesis specifically examined the sensitivity between empirically generalised LUC areal map units and their erosion severity measurements measured at a 1:10,000 map scale, compared to NZLRI's 1:50,000 scale areal map units and erosion severity values.

The South Island (Sherry River Catchment) dataset, as explained in Chapter 4, was provided by the Tasman District Council and showed an overall 69% accuracy. This is a poor agreement for a hard classification of thematic LUC surveys and is not significant when using ≥ 85% significant level proposed by Congalton (2008b, pp. 56-57). Chapter 5 results show similar findings for the North Island (Horizons Region) with a 63% overall accuracy. Poor agreement is further substantiated in both case studies with moderate Kappa values $\widehat{K} = 44\%$ for the Sherry River Catchment case Study and $\widehat{K} = 46\%$ in Horizons case study. Both Kappa statistics show moderate agreement according to Landis and Koch's (1977), but in the context of this thesis show insufficient agreement inclusively. The overall accuracy and Kappa values presented in this thesis provide evidence of high sensitivity of LUC areal map units and erosion severity measurements when generalising measurements at spatial resolution of 1:10,000, as compared to 1:50,000. These findings are consistent with Hennings (2002) who found 75% of error in soil mapping at different spatial resolutions was caused by soil variability and the remaining 25% was indicative to the degree of uncertainty from human and mechanical mapping practices.

The variance in the minimal legible areas (areal map units) displayed between the two spatial resolutions of observed variables in this thesis, a difference of ≈ 30 ha (as explained in Figure 2.4[4]), was enough to cause relatively high disagreement in areal map units and substantial heterogeneity in categorical classification. This is a classic example of the MAUP and was perpetrated because there are important erosional processes affecting the landscape, discernible at a spatial resolution seen when measuring at a map scale of 1:10,000, which are lost when measured at a coarser 1:50,000 map scale. The evidence provided in the accuracy assessments of Chapters 4 and 5 show that if LUC erosion severity measurements taken at a map scale of 1:10,000 were to be used as the underlying data of MFE's proposed ESC system, significantly different results would be found. Overall poor agreement in both case studies illustrated a significant degree of uncertainty or difference between LUC areal map units and their erosion severity measurements when testing spatial resolution sensitivity. Figure 4.5 and Figure 5.5 demonstrated the shift of erosion severity categories from the coarse NZLRI to the finer resolution (i.e., smaller map scale) LUC surveys. The map units were overlaid in both figures as well, demonstrating the drastic differences in areal extents of individual LUC map units due to empirical generalisation, which was further illustrated in Figure 4.6 and Figure 5.1. This is consistent with the literature (e.g., Bloomberg et al., 2011; Galli et al., 2008; Hennings, 2002; Lynn et al., 2009; Manderson & Palmer, 2006; Saunders & Glassey, 2007), which suggests that spatial resolution finer than 1:50,000 map scale should be used for local management decisions. The hill country and steep slopes, areas that have a higher probability of slope failure due to erosion are often where plantation forestry is most practiced; thus greater detail (i.e., finer spatial resolution) of mapping is needed (Manderson & Palmer, 2006).

It is inevitable that there are differences between the fine and coarse datasets studied in this thesis due to error introduced during the mapping processes. This error is introduced through human and mechanical means, as all maps have a degree of error. Thus, it is important to control and identify map error. Psychological, physiological, and logical errors affected representations of areal map units during the empirical generalisation of LUC map units and are common in naturally occurring lines such as rivers or other natural borders of areal map unit extents (Jenks, 1981).

Maps of the same extent but different spatial scale, as investigated in this study, represent different levels of abstraction (Li, 2007, p. 59). Substantial abstraction was apparent and quantified in this thesis, as seen in the overall accuracy reported in both Chapter 4 and 5. This was most likely due to the methodology used to empirically generalise LUC areal map units. The abstraction of areal map units and erosion severity measurements was limited by the resolution of the human eye or limitations of the “smallest visible object” (Li, 2007, p. 62). The human eye and the spatial resolution/extent that it is physically capable of was the primary tool from which empirical judgments where made. Experienced scientists then used varied protocols based on the *LUC Handbook* (Lynn et al., 2009; NZ MWD & SCRCC, 1971) to realise LUC areal map units and used the reconnaissance data available for thematic mapping of LUC erosion severity categories. When this system is implemented at different spatial resolutions, the products (i.e., LUC survey maps) will vary according to map scale. The evidence provided in this study, implies that if you use LUC data surveyed at finer resolution, substantially different erosion severity values will be predicted if that data is used in the MFE’s proposed ESC system. The sensitivity of areal map units which were empirically generalised at different spatial resolutions is an example of the scale effect, a sub-problem of the MAUP, according to Openshaw (1984b). Furthermore, erosion severity category is subjected to hierarchical shifts due to spatial extent of erosion types. This outcome is another sub-problem of the MAUP, the zoning effect. Figure 6.2 illustrates the process occurring when the human eye is used to generate LUC areal map units from reconnaissance data at different spatial resolutions.

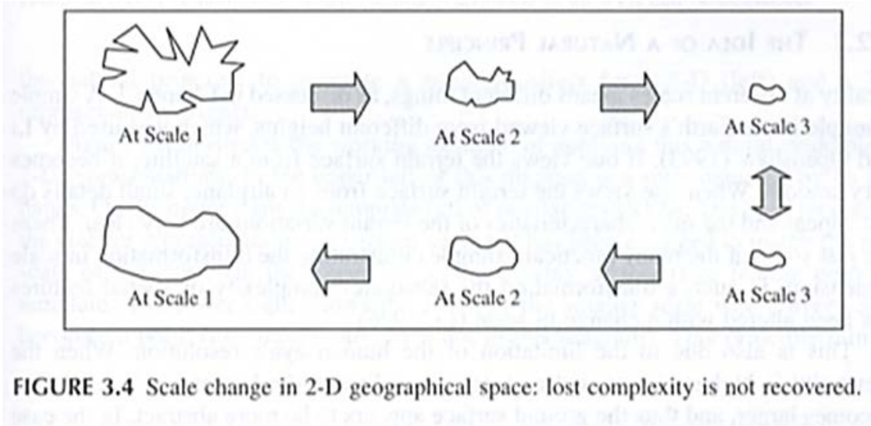

FIGURE 3.4 Scale change in 2-D geographical space: lost complexity is not recovered.

Figure 6.2: Example of the scale problem and the abstraction identified, which is causing spatial uncertainty between the LUC surveys investigated in this thesis.

(From Li, 2007, p. 61)

Scaling effects were quantified in Chapter 4 and Chapter 5 by the Producer's and User's accuracy statistics. Table 4.3 shows that the Tasman LUC survey (sample dataset) can claim that 64% of the time (Producer's accuracy), an area that was categorised by the NZLRI LUC as erosion severity class 3 was identified as such by the Tasman LUC map, with a further 32% identified by the Tasman LUC as erosion severity 2. A user of the Tasman LUC map will find that 97% (User's accuracy) of the time a point which the map says is erosion severity 3 will also be erosion severity 3 in the NZLRI LUC map. The high User's accuracy in this instance is due to the small sample size of AOIs I, J, and K which were completely classified as erosion severity 3. This was the only instance where high User's accuracy was identified in this study.

Furthermore, when looking at the error matrix in Table 4.2, substantial differences in thematic categorisation are observed across the AOIs investigated in the Sherry River catchment, when only looking at thematic occurrence and not spatial locality of erosion severity classes 2 (+55% difference) and 3 (-66% difference), when comparing the sample to the reference dataset. Chapter 5 painted a different picture as seen in Table 5.2, where high erosion severity categories sampled, that is, categories 3 and 4 had Producer's accuracies of 51% and 37%, respectively. The User's accuracies for the same erosion severity categories were 75%

and 51%, respectively. All calculations showed poor agreement, thus providing evidence that spatial resolution of areal map units and their associated erosion severity measurements are important and sensitive to changes in spatial resolution.

6.3.2 Implications

The low spatial agreement found in the accuracy assessments of both case studies presented in this thesis, illustrated a high degree of sensitivity of LUC surveys to spatial resolution. Given that the accuracy assessments conducted in this thesis showed substantial disagreement, it can be said that an ESC system produced with the NZLRI would have substantially different implications in point source erosion predictions than if a finer 1:10,000 map scale dataset was used. This would imply that if MFE's ESC system which was meant for local level management decisions were to use a local level spatial resolution (1:10,000 map scale), the ESC system could provide a better representation of point source erosion than the current regional 1:50,000 resolution.

6.3.3 Limitations

It was intended that this study would use a third sample map for spatial analysis. This map would be a systematic point sample across all AOIs of ground-truthed erosion severity measurements. While this could be perceived as just another set of empirical judgments, it would provide an estimate of actual erosion severity that can be correlated with the probability estimates of Producer's and User's accuracy; further strengthening the evidence presented in this study. Time and funding constraints precluded this work being carried out.

It was assumed that the use of common protocol (i.e., *The LUC Handbook*) and the same reconnaissance materials would reduce surveyor bias. This could be tested using LUC surveys where the same surveyors measured variables at all spatial resolutions of interest. This would prove useful for quantifying possible surveyor bias due to human subjectivity and different experience and perceptions of each surveyor. This was not done in this study, again due to time and data limitations.

Chapter 7 Summary and Conclusions

7.1 Introduction

This thesis examined the sensitivity of areal map units for MFE's ESC system to changes in spatial resolution (map scale), which will be used for local level erosion management decisions in the proposed NES for Plantation Forestry. The focus of this study was to assess whether a finer spatial resolution (i.e., 1:10,000 map scale) would provide equal or better prediction of erosion severity measurements. Nonparametric statistics and an accuracy assessment were used to assess spatial uncertainty.

7.2 Restatement of Thesis Aims and Objectives

This thesis aimed to provide an understanding of sensitivity of spatial resolution, by quantifying the level of agreement between LUC surveyed erosion severity measured at a local 1:10,000 map scale, as compared to the same unit of interest and spatial extent measured at a regional 1:50,000 map scale. To advance this aim the following objectives were stated:

1. Attempt to identify a unique discriminant parameter of erosion, which can be applied across all landscapes of NZ and be used as a model to assess the spatial uncertainty in MFE's proposed ESC system.

2. Quantify the scale-dependent uncertainty in the ESC system, through a Geographic Information System (GIS) pair-wise analysis of two finer resolution underlying datasets, against the coarser national NZLRI LUC dataset.

7.3 Summary of the Main Findings

To accomplish the listed objectives, this thesis conducted two case studies. The first case study's (i.e., The Sherry River Catchment Case Study) results were presented in Chapter 4, investigated both research questions of this study on an area located in the Tasman District of the South Island, NZ. To answer the first research question the case study used the Spearman's Ranked Correlation Coefficient (ρ) to identify any association between the morphometric parameter Melton ratio and erosion severity measured at both 1:10,000 and 1:50,000 map scales. The case study then investigated the second research question, using the Spearman's ρ in order to understand the consistency of agreement in erosion severity categorical measurements between the assessors of the Tasman LUC survey, as compared to the assessors of the NZLRI LUC survey. Then an accuracy assessment was performed comparing the same unit of interest (erosion severity categories) and spatial extent (the Sherry River Catchment Case Study AOIs) of the reference dataset (i.e., NZLRI LUC survey) to the sample dataset (i.e., Tasman LUC survey). An accuracy assessment quantified and provided a spatially valid measure of agreement between the 1:10,000 map scale Tasman LUC survey, as compared to the 1:50,000 map scale NZLRI LUC survey; thus, providing a measure of sensitivity of spatial resolution in empirically generalized LUC measurements.

The second case study's (i.e., The Horizons Case Study) results were presented in Chapter 5. While this case study also utilised a 1:10,000 map scale dataset, it looked at a broader geographical and morphological extent of erosion severity measurements within the Manawatu-Wanganui Region of the North Island, NZ. As with the first case study, this Horizons Case Study used the Spearman's Correlation Coefficient and an accuracy assessment in the same capacity to test the spatial agreement of erosion severity measurements between the sample dataset (i.e., 1:10,000 map scale Horizons LUC survey) and the reference dataset (i.e., 1:50,000 map scale NZLRI LUC survey).

7.4 Conclusions

This study identified no significant association between the Melton ratio, identified using GIS debris-flow modelling, and erosion severity measured in the Tasman LUC survey and the NZLRI LUC survey. Weak association/correlation exists between LUC erosion severity surveying and Melton ratio values calculated using Irvin's (2011) REC Debris-flow model at a local 1:10,000 map scale and regional 1:50,000 scale in the Sherry River catchment. Thus, the Melton ratio is not recommended for use as an independent discriminating parameter of erosion severity, within the context of the methodology explained in this thesis.

Given that the ESC system in the proposed NES for Plantation Forestry is a decision management tool with the intent of identifying local level erosion, this study provides evidence that higher spatial resolution, empirically generalised LUC areal map units and associated erosion severity measurements, will provide different results than MFE's current ESC system. Research suggests that the current spatial resolution of MFE's ESC systems (i.e., 1:50,000 map scale) is more suitable for regional level measurement decisions. Assuming that finer resolution data can provide a more accurate picture of reality, then this study showed that there is around 40% spatial uncertainty or disagreement, when comparing LUC surveys measured at the map scales of 1:10,000, to surveys measured at 1:50,000 scale of the same areal extent and measured unit. Evidence provided in Chapters 4 and 5 showed consistent low User's accuracy levels or individual thematic category agreement for both case studies investigated. This illustrates the shift in individual thematic category, a product of the scale effect, apparent when erosion severity was measured at a finer spatial resolution than the current ESC system. The overall accuracy and the GIS analysis shown Figure 4.5 and Figure 5.5 provided ample support of the disagreement in empirically generalised LUC areal map units; a product of the scale problem. This disagreement is easily seen when overlaying areal map units, as shown in Figure 4.6 and Figure 5.1.

It is suggested that MFE continue to improve the ESC system by using higher resolution data, which land and forest managers may already possess. If the current underlying data is used there is a high probability that in reality, when someone goes to a location on MFE's proposed ESC map for assessment of erosion severity, it will not have the same erosion severity as indicated in the ESC system.

7.5 Suggestions for Future Research

The findings of this research provide evidence that finer resolution erosion severity measurements are a necessity for the ESC system proposed in the NES for Plantation Forestry to achieve its intent. This outcome puts the economic burden and possible safety concerns as the first priorities of future research. However, erosion surveying is still in its infancy when using GIS as a tool and this study should be expanded with multiple datasets to identify trends in overall and individual class accuracy levels.

Integrating computer modelling and empirical erosion severity surveys could provide reliable and effective model for predicting the economic cost and life threatening erosion issues of NZ. Further research into developing a GIS based decision support system (e.g., Aerts, Goodchild, & Heuvelink, 2003), which integrates the NZLRI inventoried variables, as well as known erosion triggering data, which then can be indexed (e.g., Ruff & Czurda, 2008) and modelled is imperative. Spatial analysis operations, such as, Inverse Distance Weighting (IDW), Kriging, Spline, or Natural Neighbour interpolation methodology may also prove useful for integrated erosion susceptibility models.

More research is needed on connecting point source erosion susceptibility and watershed level management. ESC systems are designed to mitigate the predisposition of erosion and risk management of “on-site” effects. However, in terms of watershed management it is important to understand “off-site” effects by predicting the transference of sediment across, the landscape, as modelled by the Melton ratio for example. Chou (2010) use of the Universal Soil Loss Equations incorporated with watershed analysis models could provide insight into the integration of on-site and off-site erosion management into one dynamic model.

While quantifying the autocorrelation of areal map units was out of this study’s scope, it may prove useful to apply other spatial statistical methods such as geographically weighted regression, which take autocorrelation into account. This may provide a more accurate product in respect to neighbouring thematic and spatial interactions. Jones (1997) advocates the use of artificial intelligence techniques to produce solutions to complex problems such as erosion modelling. Smith et al. (1988) demonstrated this by applying knowledge-based system technology to planning GIS in order to generate possible LUC given a variety of environmental data sets and constraints dictated by planning policy (as cited by Jones, 1997, p. 16). This type of system could be used in the generalisation of areal units and potentially reduce the spatial resolution sensitivity introduced by human subjectivity.

There has been little study using systematic or other sampling techniques to quantify accuracy of both the NZLRI or LUC surveys. Most of the data used in the NZLRI data set was collected several decades ago. It is imperative that data be systematically updated and when technology allows, re-measured for accuracy in systematic intervals. The more accurate the data the more informed decision makers can be. In closing, future research into erosion modelling and GIS analysis in general must keep in mind the following statement by Carrara and Pike (2008):

“The quality of model input data, both landslide inventories and triggering factors, continues to attract less concern than method and technology. All too often, inferior observations collected quickly at low cost offer greater appeal than the difficult-to-acquire information most likely to explain slope instability. However, data manipulation, no matter how sophisticated, can never compensate for substandard input observations. That the lives of innocent people may be at risk by ignoring this irritating truism is all the more reason to take it seriously.”

Appendices

Appendix 1: LUC Map Units and Correspond Erosion Severities of the NZLRI and Tasman LUC Survey Within the AOIs of The Sherry River Catchment Study.

NZLRI LUC Survey		Tasman LUC Survey	
LUC Map Units	*Erosion Severity*	*LUC Map Units*	*Erosion Severity*
3e6	0	3e9	0
4s1+6w2	0	3s2	0
4s13+6e21	2	4s3	0
4s3	0	4s3+3s2	0
6e18	3	5w1	0
6e21+4s13	2	6e18	2
7e25	3	6e18+7e4	2
		6e21	2
		7e25	3
		7e4	3
		7e7	3
		7e9	3

Appendix 2: Field Investigation Checklist for Identifying Debris-flow, Adapted From Welsh (2008).

Criteria	Presence	Frequency	Intensity	Remarks
Narrow channel, small width to depth ratio				
Semi-circular to U-shaped channel				
Sinuous terraces formed by flow margins				
Channel scoured to bedrock				
Lobate areas of even age vegetation younger than the surrounding growth				
Old bark scars high on trunks and branches of trees				
Presence of scattered large, woody debris				
Coarse deposits beyond the channel on the fan				
Depositional lobes several meters high in the channel and on the fan surface				
Levees of coarse angular material aligned along the stream on upper fan				
Boulders rolled against trees on the channel banks or lodged high above stream channel				
Isolated boulders in the channel and on the fan surface with diameters >1m				
Massive boulders perched on top of finer deposits				
Deposits are massive, stratification absent, with no imbrication,				
Poorly-sorted and matrix supported deposits				
Angular to subangular clasts				
A-axis of clasts oriented parallel to flow or randomly oriented				

(as cited by Kurtz, 2012)

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